uc3m | Universidad Carlos III de Madrid

University Degree in Aerospace Engineering

Academic Year (2018-2019)

Bachelor Thesis

"Virtual Test like future tool in the Mechanical Test"

Elena Haro Correa

Jose Luis Andrés Mateos

July 2019, Leganes

SUMMARY

This thesis intends to study the viability of using virtual testing in daily work develop by the aerospace industry. In order to do that a phase of research has been done where some technical papers of studies realized by different companies are presented to see the results obtained and the benefits.

Then the program MSC.ADAMS was the one chosen for this thesis so a first approach to this software is shown. To put into practice all the new concepts and skills about ADAMS, a piece has been selected to perform a simulation.

The piece is the Gravel Deflector of the NLG of the aircraft C295. This mechanism is going to be first simplified and then several modifications are going to be performed to improve the simulation as much as possible.

Finally, a physical test has been carried out in order to have real results to which the ones of the virtual simulation can be compared.

Keywords: VT (Virtual Test), NLG (Nose Landing Gear), Prototype, Physical test, Simulation, Multibody Dynamic, ADAMS

DEDICATION

First of all, I would like to thank Airbus for bring me this opportunity in which I have been able of working in such an important company and learned so much. The development of this thesis, even if it has not been easy, has given me great satisfaction both professionally and personally. Thank you to all the people in the company that has helped me anytime, but in specially to my tutor Jose Luis Andrés Mateos.

Also all the professors from my university that were always available to help me with any doubts, no matter how much work they had. And that is a reflect of the incredible people that forms the Universidad Carlos III de Madrid.

Lastly, but not for that less important, the biggest thanks goes for my family. They have been, are and will be my support during all my decisions in life. Because things have not been easy all the time but they will be always there for me.

In difficult times where it seems difficult to see the end, I like to remember a quote from Alice Morse Earle, that is:

"Every day may not be good, but there is something good in every day"

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Motivation of work

This work has been developed during a 5 months internship in Airbus Defence and Space, located at Getafe. The placement was with the Mechanical Test Department.

This thesis studies the viability of the use of virtual testing software in the aerospace industry in order to improve engineering efficiency apart from reduce time and cost by evaluating the whole performance of the system.

The need to implement this kind of software is motivated by reduce production time and to improve the performance and reliability of the products. Thanks to this tool the execution of the desired piece can be evaluated before producing it, so the malfunction or mistake in the design can be found easily. Also an advantage is the possibility to explore the performance of hundreds or thousands of different designs with modifications in a short period of time and without spending the money and effort that it would cost to do it physically.

In order to rely in virtual prototyping, several studies had been done where comparing the results obtained from a test of a physical mechanism with the ones obtained in the simulation process.

After all trial and error tests, the use and reliability in the results given by the virtual prototypes has increased considerably over the years. Several sectors has include this study in a fundamental part of the first step in process of manufacture a piece, as it will be seen through this thesis.

One of the most used system is the Multibody Dynamic and motion analysis software, in which the dynamic behaviour of a rigid or flexible part is study, or an assembly of them, when submitted to different loads or constraints. Some applications of this software are used in Aeronautics, Robotics, Military applications, Bio-mechanics and a wide range more.

This work is not only a motivation of Airbus Spain but Airbus as a worldwide company. It can be seen in a technical paper in which it is said that "Airbus High System Lift Test Department has been continuously working for more than couple of years to introduce Virtual Testing as an additional, and equivalent test means" [1] so Airbus Germany is also working in the development of Virtual Test as a future reliable tool.

1.2. Goals

Even if this project is still in the development phase, the goals are ambitious. The main desire is to develop the skills necessary to use the tools used during this thesis and get positive results in the viability of virtual testing in the industry. The software chose for this project has been "MSC ADAMS", after a study and analyze phase which is going to be explain latter in the chapter "Analysis of the current situation".

The company Airbus is interested in introducing a phase of virtual analysis in the Mechanical Test department, in order to reduce the pressure in their engineers to develop and produce better and faster tests while reducing their overall cost so new methods have to be developed in order to replace physical mechanical test with ones realized using virtual testing.

Two important aspects have to be taken into account when developing the method. The optimization of the Pyramid of Test is the first one while reducing the risk to perform the Full-Scale. These are the main drawbacks for the company.

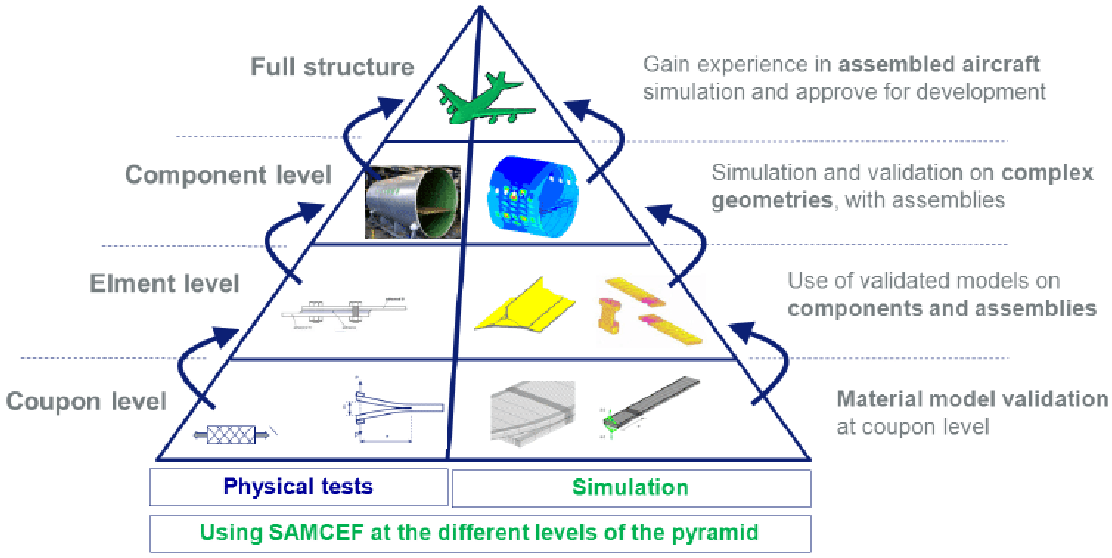


Fig. 1.1. Pyramid of tests divided in physical and virtual testing [2]

The previous figure shows an image from [2]. The pyramid is divided in physical and simulation tests in different levels. Actually all the simulation tests need to be compared with the results of physical tests in order to know the precision of the results obtained. The first one would be the coupon test in which just material is validated so it is the lower level in which every project starts. After that, the elements can be validated so components by itself or assemblies are now used. This second level is the one in which this project is focused.

Then, more complex geometries are in the next level just before the final peak in which the full structure is situated.

Obviously the long term goal is to reach the peak of the pyramid where full test structures can be validated with simulations but until then, a long ride is still ahead of us. This project is still in the development phase so right now the most important thing is to examine the current situation and acquire knowledge of the available programs that exist and compare them in order to find the most suitable one.

The first step to achieve this goal is to check the available softwares and investigate the possible potential that they could have in the industry. Then, some projects should be started where different design concepts can be taken into account. Latter, the solutions obtained with this process need to be evaluated to reduce the risk. Finally, at the certification part, virtual test offers the possibility of an alternative to the actual certification process that are use in test to full scale.

At is has been already said, this thesis is focused in the second level of the pyramid test validation. So the piece of interest that is going to be analyzed in ADAMS is a simplification of the gravel reflector of the nose landing gear.

The piece of study corresponds to the nose landing gear of the aircraft C295. This landing gear is of special interest because it has been designed to land in mud areas and the aircraft has a camera installed behind it and the purpose of the gravel deflector is to prevent the lent of the camera to get dirty or broken during the landing. The Figure 1.2 and Figure 1.3 show the design of the landing gear in CATIAV5 and the gravel deflector.

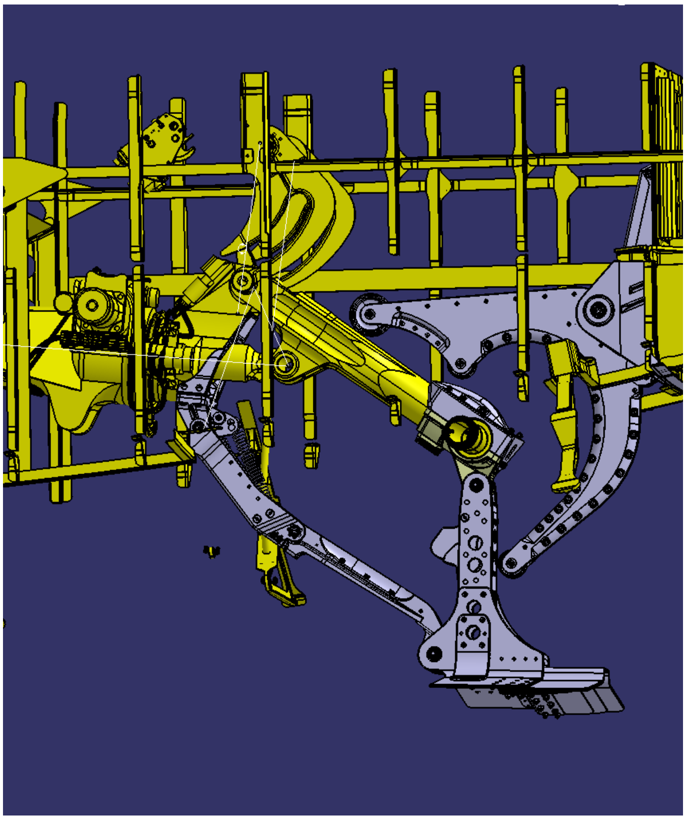


Fig. 1.2. Complete model of the landing gear in CATIA in extended configuration

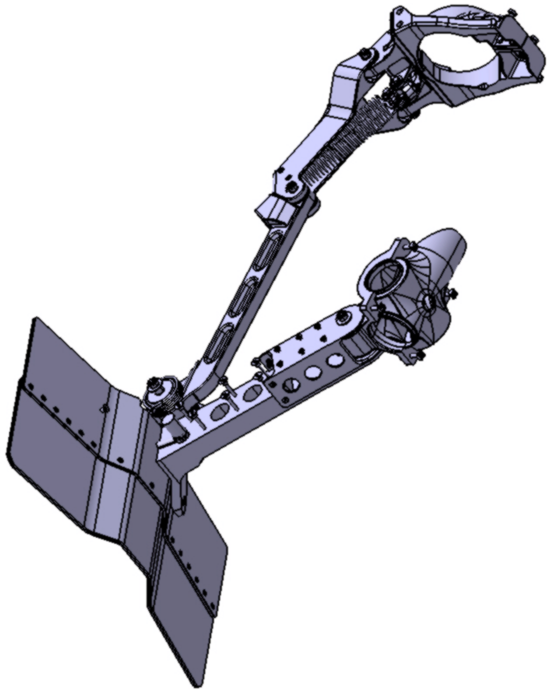


Fig. 1.3. Parts of interest of the gravel deflector for the thesis

In the first picture the whole design can be visualized while in the second one just the pieces of our interest are shown. The pieces shown are the one that are going to be simplified during the analysis in ADAMS. In the analysis our principal requirement is to obtain the minimum force that has to be applied in order to broke the structure and the landing gear can be retracted and go up to be kept in the fuselage.

1.3. Content of the thesis

Several chapters have been created in order to distribute in a proper way the work done and it would be easy to understand for the reader.

The first chapter "Introduction" explain the motivation of this work and the main objectives that wanted to be achieved so it gives a general view of the whole project. It also explain the content of the different chapters.

In the second chapter "Phases of the project" there is a brief description of the different steps that this thesis has had.

The third one "Analysis of the current situation" shows the state of the art of the Virtual Testing. After that, several technical papers are examined in which different softwares have been used in order to be able to compare between them and know its different advantages that they can offer. Finally, after that phase of research, it is explained which is the software selected for the realization of this thesis. For that, the main characteristic and the different modules available are described.

Then in the fourth chapter, "Simulation of the piece of study and results", the procedure followed is described and the results obtained during the simulation and analysis of the desired piece are analyzed and commented. During the procedure to do the piece, an analytic study is done to compute the forces and the following creation of the piece in ADAMS are explained, with the corresponding explanation of the modules used.

The fifth chapter is devoted to the "Physical test of the piece of study" where it is shown the mechanical test that has been performed in order to be able to compare the results with the ones of the previous chapter.

Lastly, in the sixth chapter "Conclusions" the whole project is reviewed and future developments are summarized here.

Then it can be found the "Bibliography" where are cited all the documents that have helped in the development of this project. Finally, there have been created several annexes in which different information can be found.

Annex I contains information about an estimation of the overall budget of this project. Taking into account the cost of the project developed with virtual testing and the cost of doing just a physical test.

Annex II where the "Regulatory Framework" explains the main military specifications that the pieces need to follow and the requirements of the design.

2. PHASES OF THE PROJECT

In order to accomplish the previous goals, the first thing to do when facing an engineering project is to define the different phases that you have to do in order to get the final results. The most important thing during the whole thesis is organization so anything is forgot and of course, validation in every step.

- The first thing before getting started with the project has been a phase of collecting documents. This part has been fundamental for the development of the thesis because a state of the art is necessary in order to locate yourself in the right scenario before doing anything.
  This gives the perfect understanding of the current situation and set more clear the goals to achieve. Several examples of others industries have been found and are going to be described in the next chapter.
  This phase has not finished during the whole project because the learning has been constant considering that the main goal was to know the real situation of virtual testing and see how it is focused for the future and get a conclusion about if it is worthy or not to use it.

- After that, a depth research of the MSC ADAMS program was also necessary because this tool was completely new for me. This learning process was focused mainly in ADAMS/View and ADAMS/PostProcessor modules which have been used during this thesis and also ADAMS/Flex.
  This phase was carried out thanks to the guide and solved problems that MSC Company has available online for the interested users in learning how to use its program, and they have been very useful.

- Understanding the principles of the mechanism that it was going to be simplified during the analysis was so important. During this phase a simplified mechanism composed by links and springs was study in order to compute the required forces of the springs to have an static and in equilibrium mechanism.

- Once the basis of the mechanism was understood, the develop of the mechanism in ADAMS was next. In this phase, the first attempt was to create the simplified mechanism in ADAMS also with links and springs as in the previous step in order to verify the results obtained during the analytically phase.

- Study the results was the last phase to accomplish during the thesis. Once the simulations were carried, ADAMS/PostProcessor gives the results so the graphs can be compared in the different cases and see if the results obtained were satisfied or some modifications should be done.

- Also the development of the physical test has been done in order to compare these results with the ones previously obtained with the simulation in ADAMS.

A block diagram has been created in order to summarized the different phases, previously explained, as it is shown by the next figure:

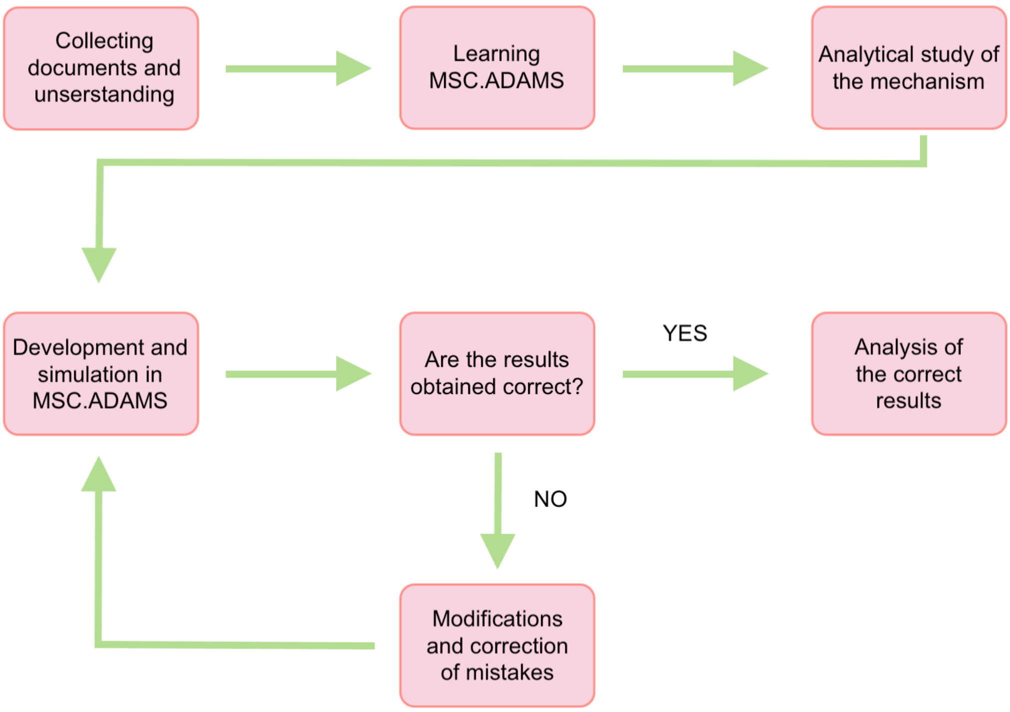


Fig. 2.1. Block diagrams of the thesis phases

3. ANALYSIS OF THE CURRENT SITUATION

Computer simulations started a long way ago, it can be said that in the late 40's and early 50's some companies started to have computers in their offices but they were not yet a very useful tool because simulations took too long and very qualified people were needed. But a huge development occurred when in 1957, FORTRAN was created by IBM. Thank to that programming code some areas as numerical weather prediction, finite element analysis or computational fluid dynamics (CFD) have been developed. All that information has been obtained from [3]

Computational fluid dynamics (CFD) plays a key roll in the aerospace industry. As it can be seen in [4]. It has been used in different kind of design and analysis for aerodynamic shape, aerodynamic forces and noise propagation models between some. Obviously the normalization of using CFD in this industry has been gradual and nowadays CFD results are compared directly with flight test information and the test in wind tunnels are becoming less used every time. Such is the acceptance of this tool that even that the Federal Aviation Administration (FAA) tends to agrees with it.

There have been developed so many different programs in order to improve the design, analysis and testing phase. Some of the most common software are:

- Ansys
- Abaqus
- SolidWorks
- Simulia
- FlexSim
- MSC Apex

- Matlab
- 20Sim

And much more can be found in [5] depending on the type of systems and simulation that the client is interested in.

So in order to do a deeper study about the state of this tool, several technical papers have been analyzed and some of them are here summarized in order to give the reader a general vision of the virtual testing utilities and its benefits.

3.1. BMW Car crash

The first example of a document has been "Predictive Crashworthiness Simulation in a Virtual design Process without Hardware Testing" [6] created by Jürgen Lescheticky, Hariaokto Hooputra, and Doris Ruckdeschel for the BMW Group in Munich.

This has been one of the most interesting articles that I have found because it reflects perfectly the background that is needed in order to fully establish the use of virtual testing in a company. It is said that BMW decided to start using virtual testing for the issues related to passive safety 13 years ago, so obviously it is a very long process. And in 2009 they established a new test bench in order to check the results obtained during the simulation and the quality of those results, which is still obviously necessary.

So the first thing that it can be obtained just from that information is that if a company wants to introduce the use of virtual test in their daily work they have to be aware that it takes a lot of time. It is said that for BMW it took several years of researching to find the perfect program that would fit all their needs and the first project was done in 2004 and it was not until 2006 when the migration was complete. So the first thing is to have a team expertise in the desired program. Then, it would be necessary to do physical tests of the simulation in order to compare the results obtained by both methods.

"This paper intends to demonstrate some of the capabilities of ABAQUS/Explicit for crashworthiness and occupant safety, with a strong focus on predictiveness and reliability. These factors are prerequisites for an efficient, cost-effective vehicle development process that relies less and less on physical prototypes and testing" [6]. So obviously the main concern is not just the full vehicle model simulation but the detailed behaviors of its components and connections. But the main goal of the work behind this paper is predictiveness which would lead to a huge reduce in time and cost.

The document is divided mainly in predictiveness on component models and then predictiveness of full car crash models, as it is normal if we look at the pyramid from Figure 1.1.

The first results are from the comparison of spot weld failure where the Figure 3.1 [6] shows the three main groups in which the fracture modes are categorized according to EN ISO 14329.

1

Fig. 3.1. Groups for resistance spot welds [6]

It can be seen in the Figure 3.2 [6] the simulation and the physical model and the correlation between simulation and experiments results, from which the results are a good approximation of the reality .

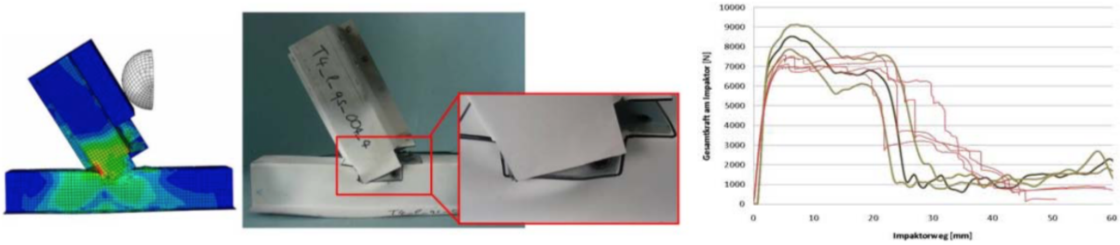


Fig. 3.2. T-Joint component test results [6]

After that "Material Failure Predictions Using the IDS Failure Criteria" [6] is done. IDS means for Instability, Ductile and Shear fracture. And it has been taken as a reference [7] were a "comprehensive approach for predicting failure of structural components caused by any combination of these mechanism" [6]. So this failure criteria is used in Abaqus to "modeling progressive image and failure of ductile metals" [6]. So the validation has been done with an study of the behavior of a B-pillar, so the comparison and the force-deflection curve can be seen in Figure 3.3 and Figure 3.4:

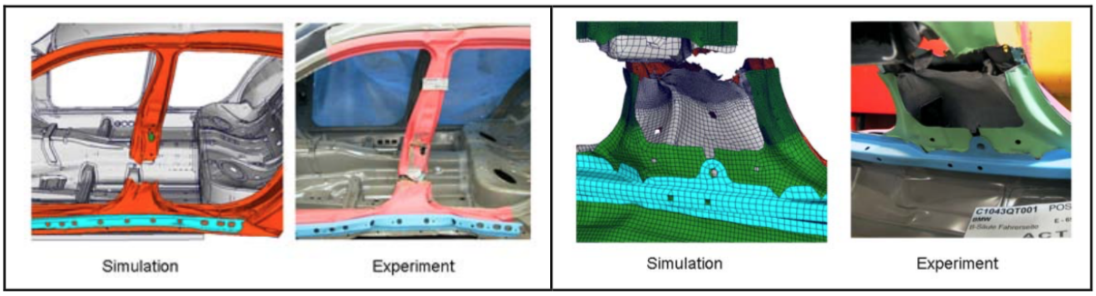


Fig. 3.3. Fracture pattern initiated by instability from test and simulation [6]

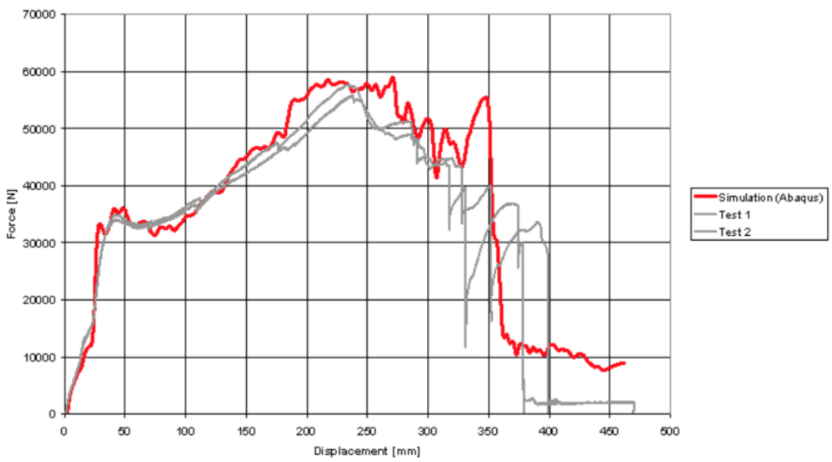
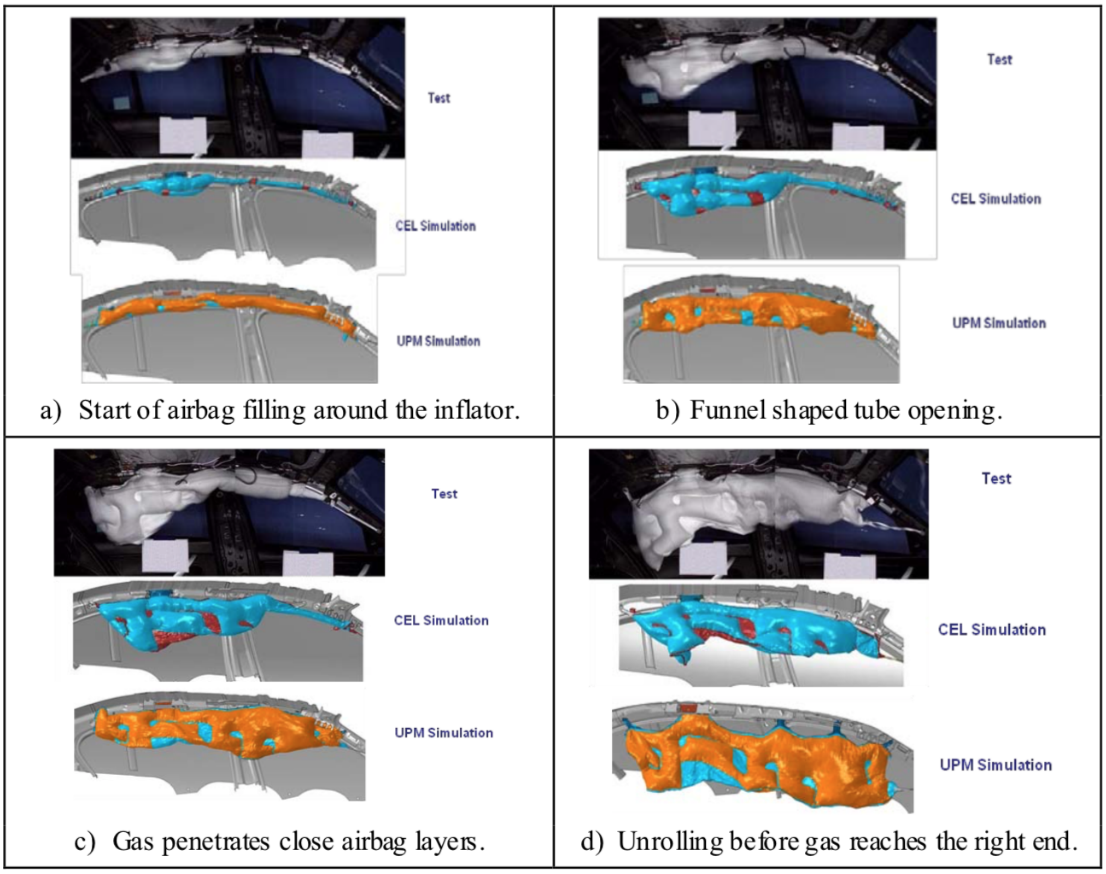


Fig. 3.4. Force-deflection curve from test and simulation [6]

Finally the simulation of the airbags is going to be analyzed, which is focused mainly in two working points: full deployed state and partially deployed state. It has to be remarked that during the deployment of the airbag the pressure distribution inside has to be simulated. In the case of full deployed airbags "uniform pressure method" (UPM) is valid because the gases are distributed homogeneously and this makes the simulation much easier. But the difficult study is when the airbags are just partially deployed so the distribution of the air inside is not homogeneous anymore so the coupled Eulerian-Lagrangian (CEL) are provided in Abaqus and it is going to be used in the second case [6].



a) Start of airbag filling around the inflator.
b) Funnel shaped tube opening.
c) Gas penetrates close airbag layers.
d) Unrolling before gas reaches the right end.

Fig. 3.5. Characteristic airbag shapes in test and simulation [6]

In the previous sequence of images [6] the results for the physical test, the simulation with CEL integrated and the ones using UPM procedure are shown. The results obtained using CEL are more accurate to the real one in especial during the deployment phase when the layers of fabric are closely folded but from the test it is said that "SIMULIA development of the CEL capability continues, and is expected to result in a very powerful tool for the design of airbags and the interaction with their environment during the development phase" [6], so some aspects can be improved in order to get more accurate results.

After these three simulations for components models the next step would be the "Predictiveness of Full Car Crash Models" [6]. In this part all the elements, material behavior and connectors have to be defined properly in order to obtain results as much accurate as possible. In pages 9 and 10 from [6] it can be seen how the simulation has improved when the failure mechanism is taken into account. Before introducing failure mechanism the predicted intrusion was 30 percent less than the real one and when talking about safety of people 30 percent is not acceptable. But in the image below it can be seen the huge impact of include failure mechanism in the model, but SIMULIA and BMW are still working in improving the simulations in order to eliminate the experimental tests.

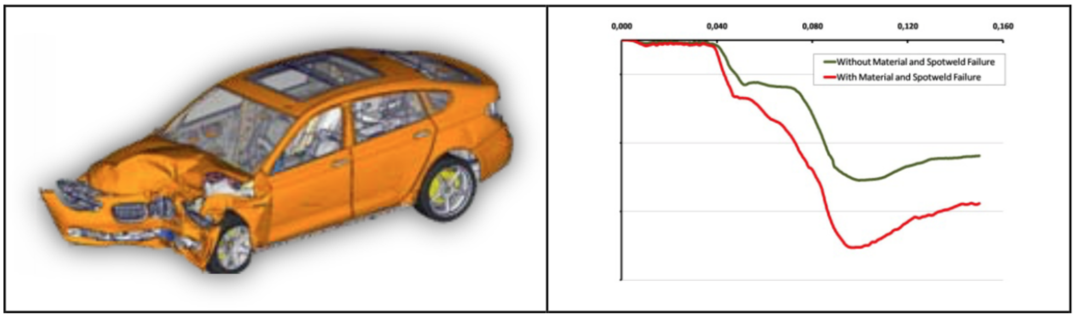


Fig. 3.6. Firewall intrusion results with old and new modelling [6]

As it was said before not only the global deformation is important but also the local effect on pieces because of the material failure and joints. "For that reason a model for an entire car is now built up to include about 3.5 million elements" [6]. Next figure 3.7 shows how the set up of a model includes mapped parts with data from deep drawing, material failure definition, spot welds and adhesive definitions with failure.

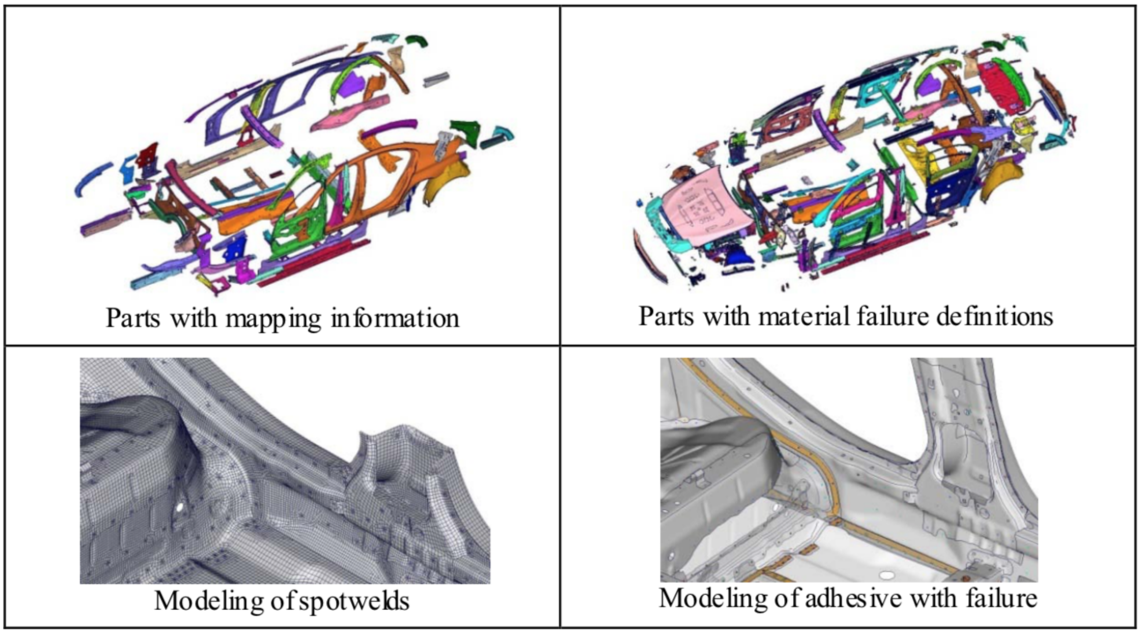


Fig. 3.7. Characteristic airbag shapes in test and simulation [6]

"The global deformation can be characterized as the global condition of the BMW after the car has been relaxed after the crash" [6]. That is shown in the following figure for different steps in time and perspective. Another advantage of the simulation is that a lot of data is available during the running time and about the entire model, while when doing a physical test only a few parameters are obtained and most of the data is then extracted from the video recorded.

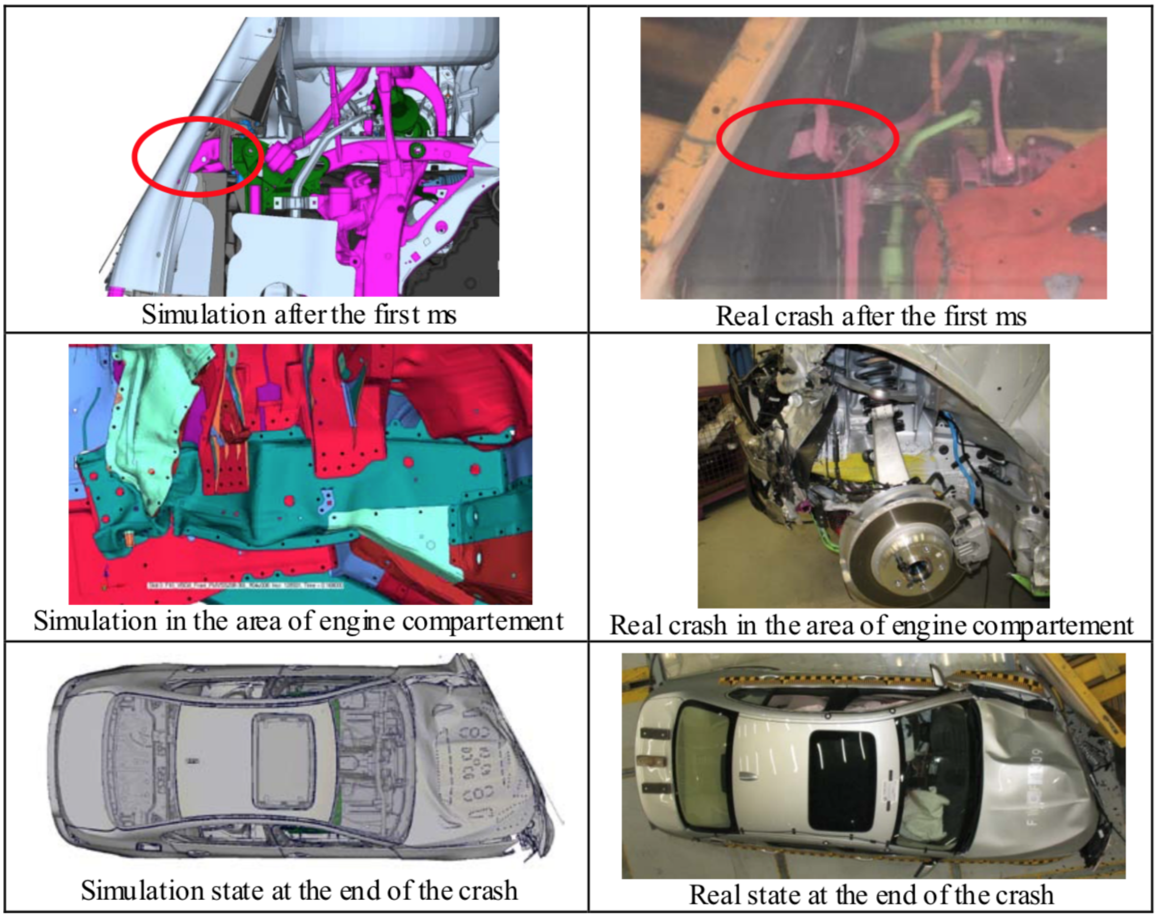


Fig. 3.8. Deformation for 30degrees frontal impact [6]

When looking at the local deformation, "a formula has been developed to calculate the required failure parameters for each combination, based on a limited number of experiments as well as the diameter of the sport weld" [6], when talking about combinations it refers to the material and panel thickness that are joined by spot welding because in every car model there are several hundred combinations. So finally the following two figures show the spot weld failure (Figure 15 in [6]) and the prediction of crack initiation (Figure 16).

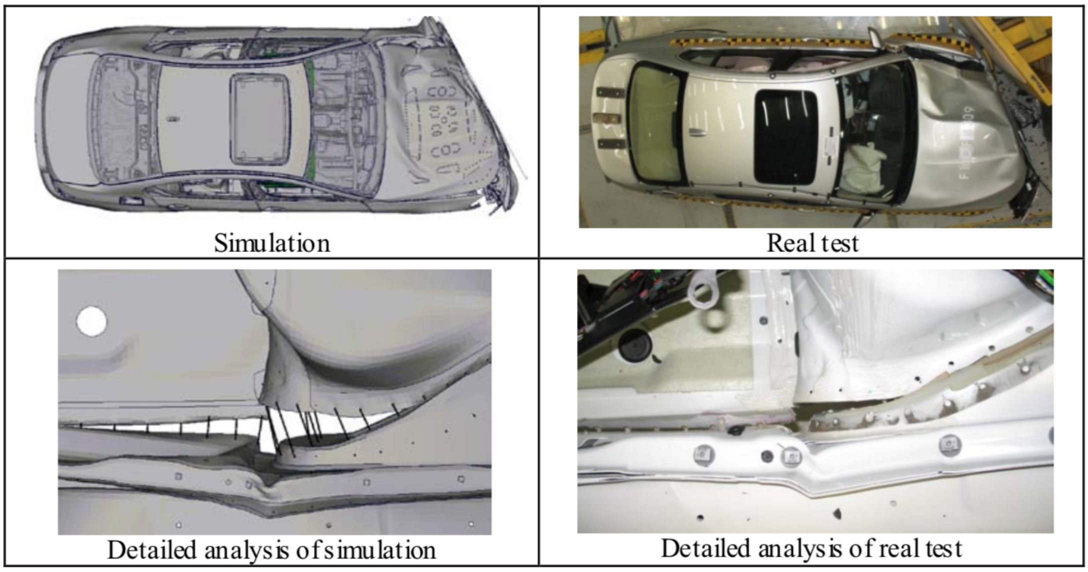


Fig. 3.9. Spot weld failure [6]

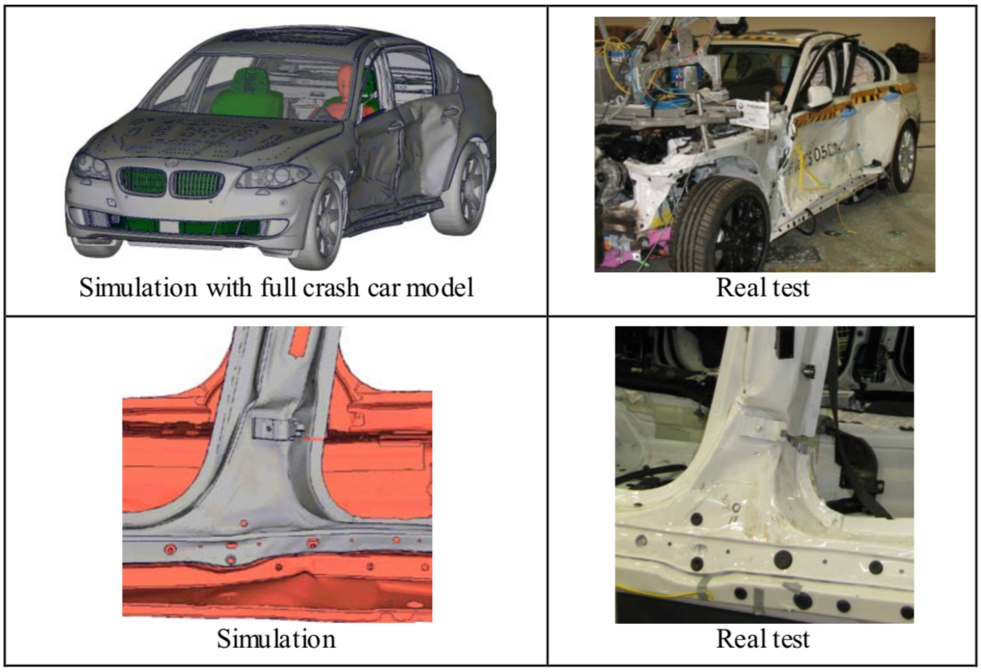


Fig. 3.10. Prediction of crack initiation [6]

The previous figures that have been analyzed show how accurate are the results obtained with the simulation using ABAQUS/Explicit when compared with the ones obtained during the physical tests. And that is the information that is more relevant for this thesis where the main goal is to study the viability of using virtual testing and in BMW it looks like they already did research as I am doing now and they established that ABAQUS give enough accurate and realistic results so a complete migration for passive safety tools has been done. If someone is more interested in the article [6], it has been done also special investigations in order to investigate the numerical sensibility for the benchmark models and also the stability. So in conclusion, "the benefits can be quantified by cost savings measured in millions of Euros and months of product development time" [6].

3.2. Goal: "Virtual" Perfection

The next article that is going to be analyzed was published in the magazine Automotive Design and can be found in [8] and corresponds to the number publishes in September 2015. This is a magazine that is produced by SAE international (Society of Automotive Engineer) and in its website a lot of editions of different magazines can be found with very interesting articles.

This article [9] questioned the need that the simulations should be 100 percent accurate and the drawbacks that it can have. According to Clement Dumand from PSA Research and Advanced Engineering "it's not just the time saved arriving at a given solution, but the ability to investigate numerous other avenues quickly before discarding the unworkable for genuine alternatives" [9]. It is also said that programs as "Exa Corporation's PowerFLOW Optimisation Solution" [9] give very good accurate solutions. This program is based on CAD-CAM methodology.

More information about CAD / CAM (computer-aided design and computer-aided manufacturing) can be obtained in [10]. It is the software used during the design and manufacturing process of products. In addition, it involves computer technologies for design documentation. The main advantage of using CAM is that it uses the models created in CAD to produce the necessary trajectories of the tools to convert the designs into physical pieces.

In the other hand, according to Convergent Science's Rob Kaczmarek, it is not realistic to pretend to obtain simulations fully accurate. "It's impractical to get a CFD model 100 percent accurate, or even 99 percent, because you're spending so much time running the model that it negates the accuracy" he states [9].

So until here, what we can get from the paper is that mostly every step of the product can be simulated and thanks to that the quality of the solutions is improved and several modifications can be tested quickly but if the models are intended to be 100 percent accurate the advantage of using virtual testing disappear because the time running would be so long and also the time dedicated to improve the model.

Then, an example is presented, the use of Adams-Marc co-simulation, which is another utility of ADAMS as it will be described latter. Adams-Marc co-simulation has been used during the development of the Volvo S80 by the technical expert in CAE durability, Anders Wirje [9].

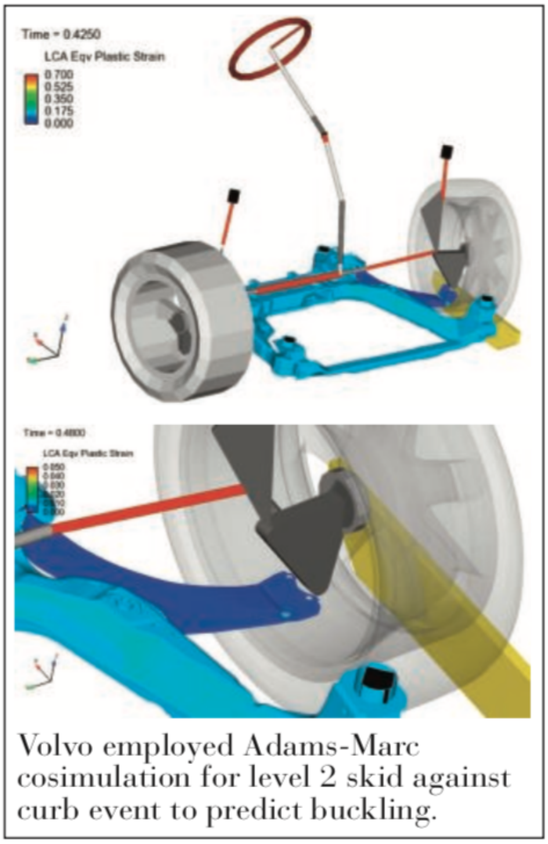


Fig. 3.11. Adams-Marc-co-simulation view for the Volvo S80 [9]

"During setting the co-simulation model for the skid against curb load case, the Marc model contains the lower control arm and bushings connecting it to the sub-frame. Then, "We were able to reduce the cost and time involved in suspension development by performing product development more accurately from the beginning, so fewer prototype verification cycles were required, prior to full physical verification being performed at the end of the project", explained Wirje [9].

After that, another example in which virtual testing has been beneficial during the development has been for the new software of Total Human Model for Safety (THUMS) created by Toyota [9].

With THUMS the muscles can be modelled so the simulation predicts the body attitude for the occupants of the car, this tool allows a deeper detailed analysis of the possible injuries that can occur during a collision, because dummies occupants could not be simulated in that way.

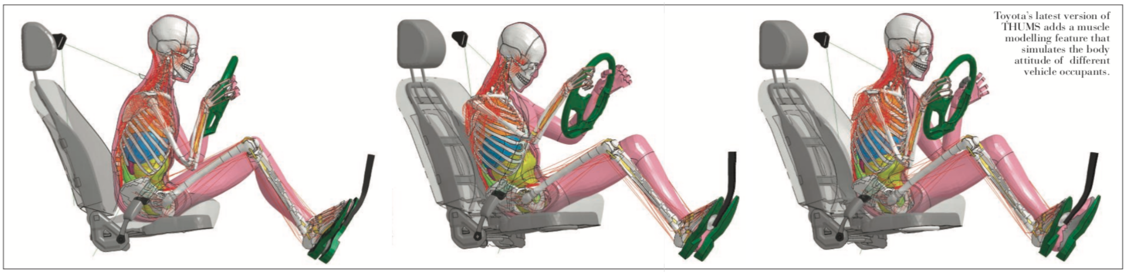


Fig. 3.12. Visualization of the muscle modelling for THUMS [9]

With this new version, it also allows changes prior to the impact so the performance of the designed passive safety tools can be analyzed in detail in order to improve them and new safety products can be development to provide a better protection for the occupants of the vehicle.

THUMS Version 5, was the latest version by the time the article was wrote, and it was already adopted by others cars manufacturers. Now doing a little bit of research, a new version has been launched, THUMS Version 6 was released on February 2019 [11].

"The new software features internal organ modeling and a new muscle model that simulates a variety of occupant postures, including braced and relaxed, permitting a more detailed analysis by anticipating various occupant postures as the widespread deployment of automated vehicles continues to advance" [12].

Finally, the evolution of THUMS can be seen in the following image.

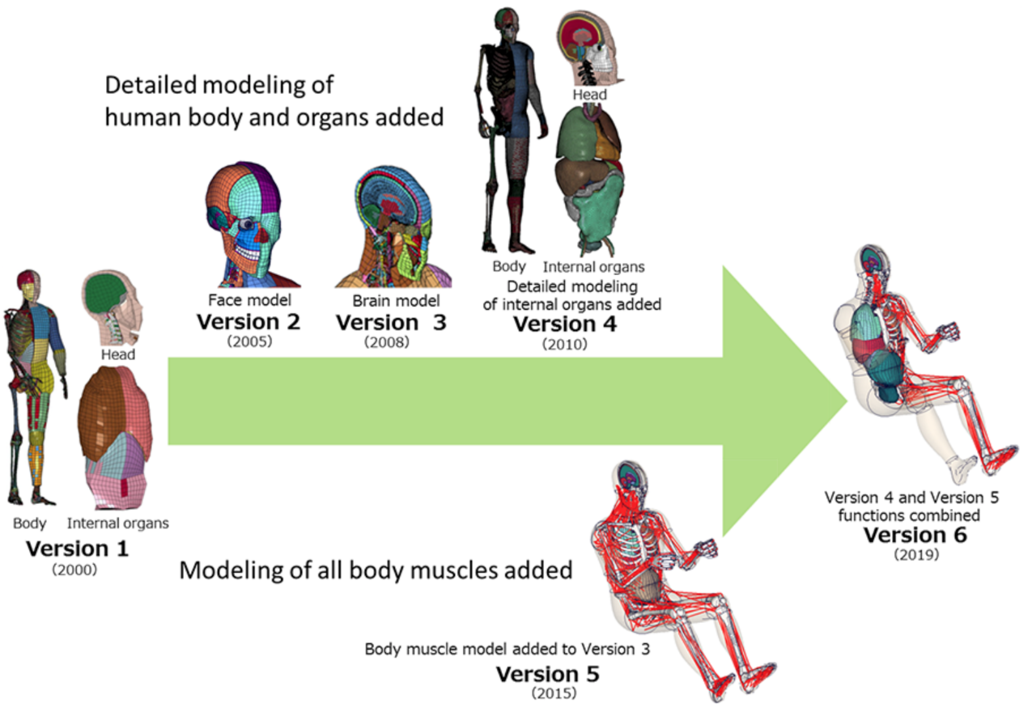


Fig. 3.13. Evolution of THUMS over the years [12]

With the information that has been obtained from the article of Automotive Design magazine, it can be clearly state that the applications of virtual testing are so extensive and most of the companies are inverting money in research and testing in order to check the results obtained. Most of the software has been in process of development and improvement for years, as is the case of THUMS, which Toyota started to investigate in 1997 and it was not until 2000 when the first version was released, and today five more versions have been necessary in order to get more accurate performance [9].

3.3. Hydro-mechanical Modelling of the Airbus A380 Nose Landing Gear Extension/Retraction Systems

This subsection is dedicated for a thesis made by Gabriele Bernardini in collaboration with the university of Pisa and Airbus UK [13].

It has been done with the Simulation and Modelling groups of Airbus in order to make a study of the hydro-mechanical nose landing gear extension/retraction system of A380 using ADAMS, the same program that Airbus Spain wants to introduce.

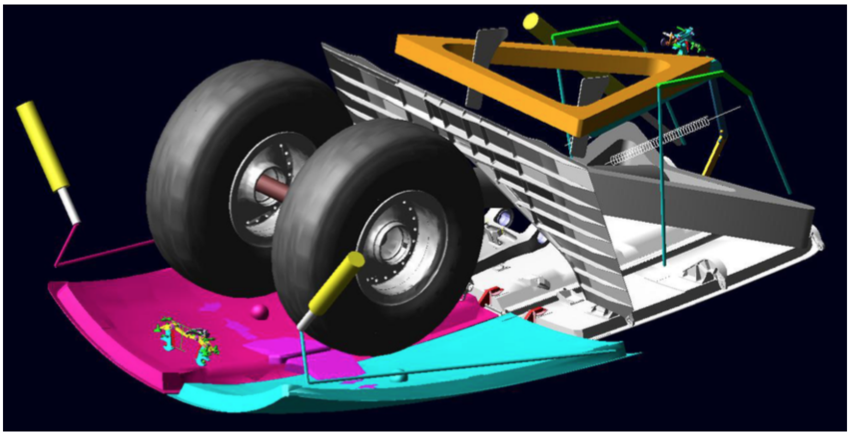


Fig. 3.14. Retracted configuration of the landing gear [13]

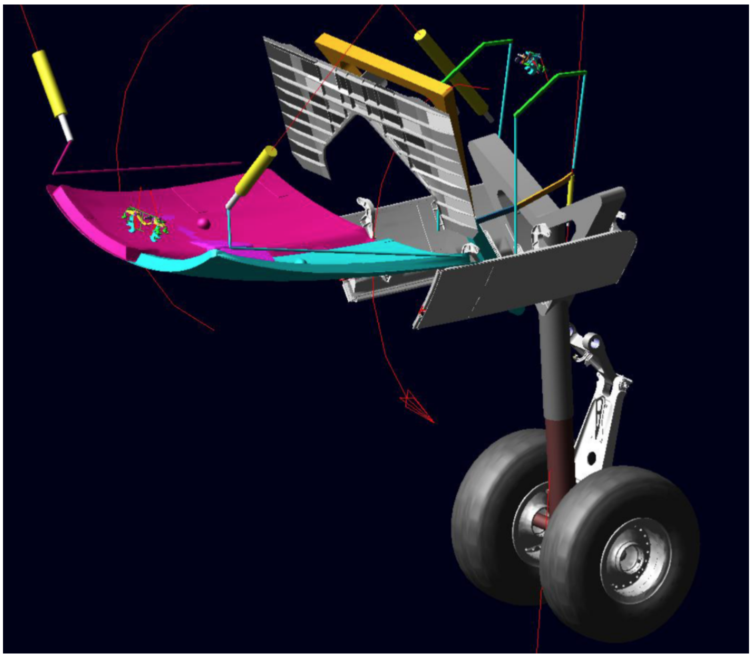


Fig. 3.15. Extended configuration of the landing gear [13]

This model, that can be seen in the previous images, was simplified in ADAMS, taking into account all the mechanical parts that are mainly involved and the masses have been properly defined [13]. This is the easy way to start in the virtual testing environment and is the same that is going to be done in this thesis with the gravel deflector for the landing gear of the aircraft C295.

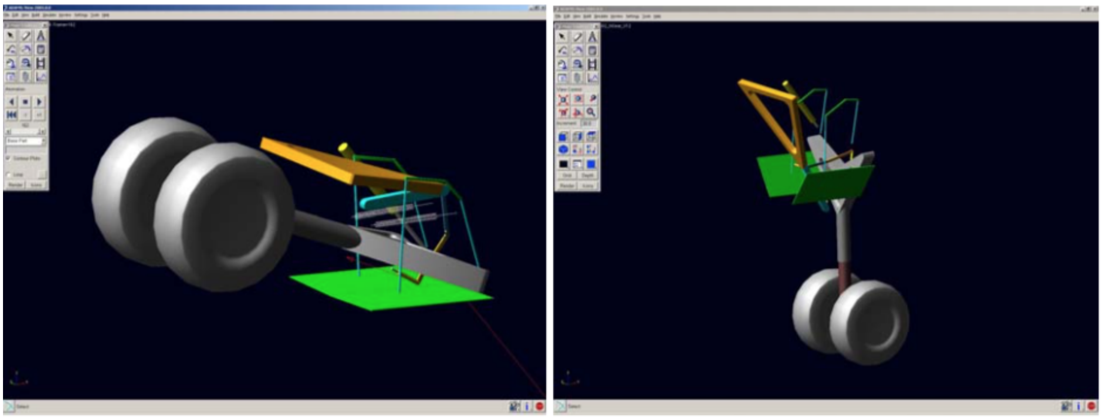


Fig. 3.16. Retracted and extended simplified models of the landing gear in ADAMS [13]

The most important feature about this thesis is not the design of the model in ADAMS because the model was given to the author already built. The thing that is interesting to review is the configuration of the Hydro-mechanical model of the landing gear. The latest was configured with AMESim and then the information is introduced into ADAMS.

Firstly, a definition of the hydraulic power system is needed and in [13] in section "2.1-Sources of information" is said that ADAMS/Hydraulic, which is another toolbox from MSC.ADAMS, could perfectly work for that purpose but instead AMESim software was used. The general architecture for the hydraulic model follows the next structure:

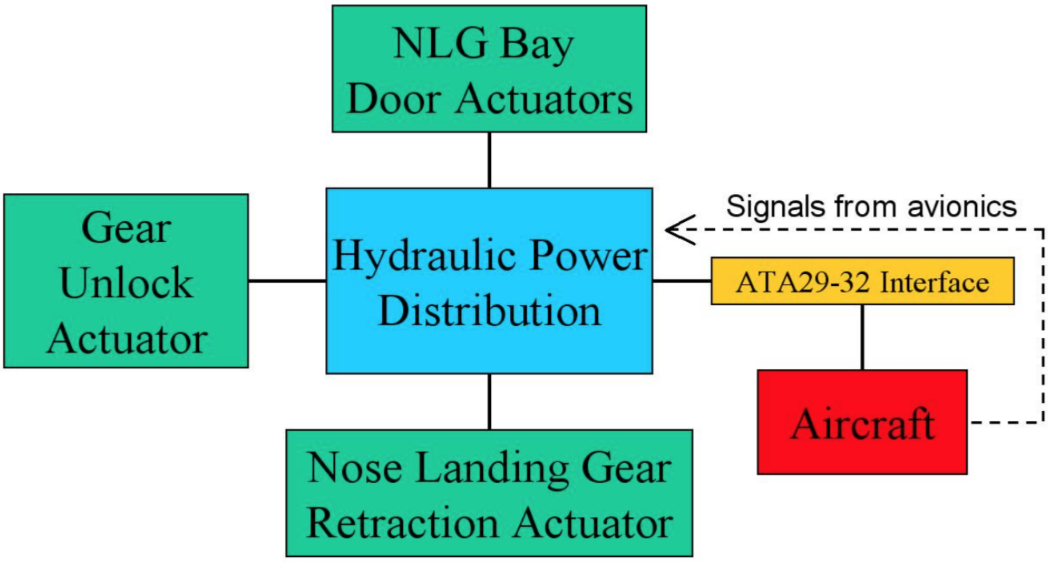


Fig. 3.17. General architecture for the hydraulic model [13]

During the thesis of interest the different subsystems that compose the general structure are explained in detail, its functions and how they have been defined. But that information is out of the scope of this thesis because the important here right now is not how every system is defined, but instead knowing that those kind of systems can be defined in one interface and then be transferred into ADAMS and model the whole system in a better way.

So in order to check that everything works fine, a co-simulation has been done where both models have to interface together and run at the same time. And there are several method that can be used for that purpose, and they are:

- **ADAMS to AMESim Full Export**

  Using this method, AMESim integrates the equations while ADAMS evaluate them. "This means that ADAMS calculates derivatives and other outputs, to be passed to AMESim solver at fixed time steps, defined by the communication interval. AMESim, moreover, acts as a user interface to the simulation" [13].

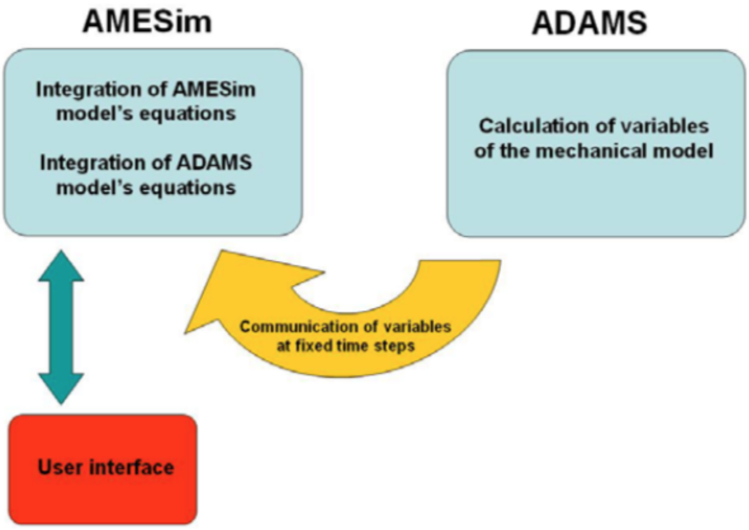


Fig. 3.18. ADAMS to AMESim Full Export [13]

But the main problem here is that AMESim is designed for hydraulic problems so in this way it will receive mechanical equations, so probably this is not the better option in these kind of problems.

- **AMESim to ADAMS Full Export**

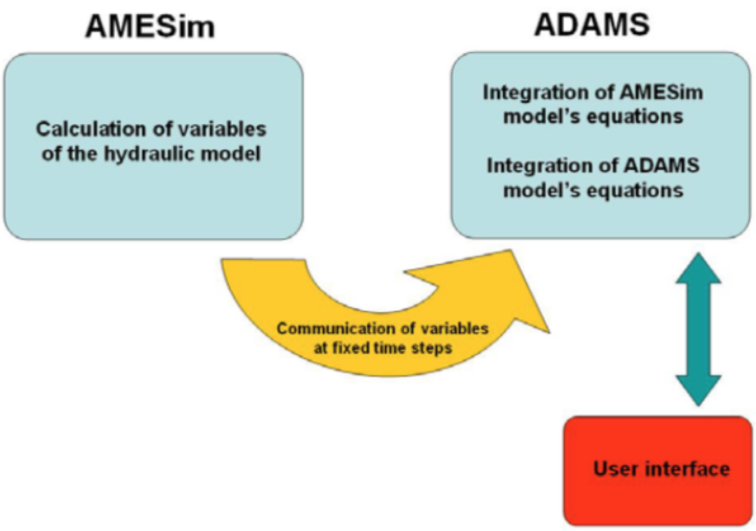


Fig. 3.19. AMESim to ADAMS Full Export [13]

As it can be seen this method is like the first one but in the inverse way. Here the equations are integrated by ADAMS while AMESim is the evaluator now; "moreover ADAMS acts as a user interface" [13]. But numerical problems may arise again because ADAMS works well for multi-body systems but in this case the numerical equations are from the hydraulic power system and those are not similar to multi-body ones.

- **Co-Simulation from AMESim**

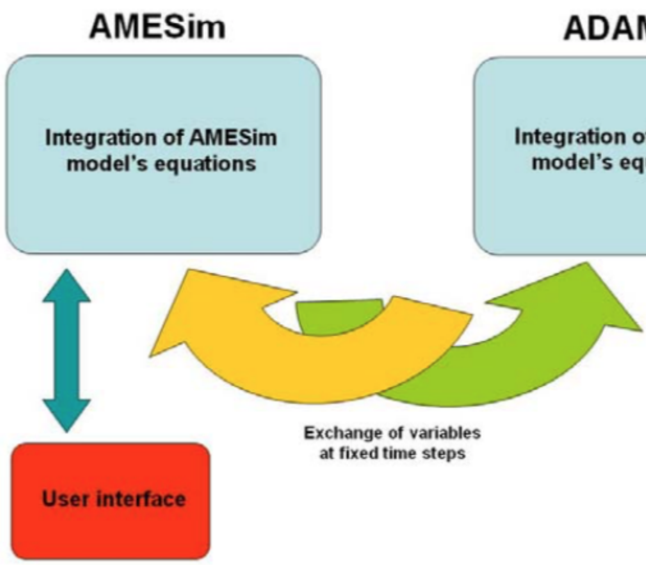


Fig. 3.20. General architecture for the hydraulic model [13]

Using co-simulation means that both systems are running with their proper set of equations and they shear information at a given time, which is known as communication interval. So they receive information and they work with that information until next interval arrived with new data. The main drawback of this method is finding a proper communication interval because each method works with different step size, without taking into account the other program.

- **Co-Simulation from ADAMS**

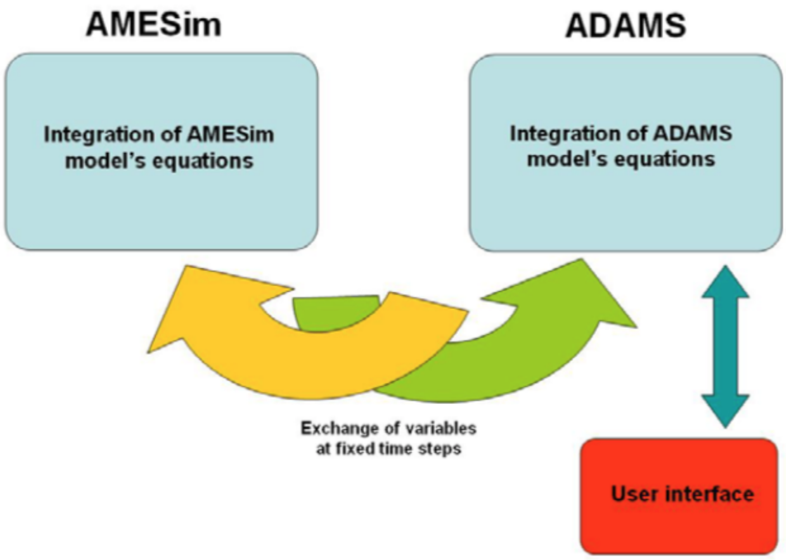


Fig. 3.21. General architecture for the hydraulic model [13]

In this method the difference with the previous one is that ADAMS is the user interface during the simulation process.

This last method was the chosen for the article because the simulation was controlled directly by ADAMS which is easier and the data could be transferred to ADAMS/Postprocessor too. In the paper it also explained that all four methods were tested but only the ones using co-simulation works good and in a decent time.

There is a section in the paper, "2.4.5- Setup of the mechanical model for the co-simulation" [13]. Where it is explained how inputs and outputs are identified and how the hydraulic forces of the actuator are calculated by AMESim and then transferred to ADAMS to be applied to the mechanical components and then visualize the simulation and the behaviour of the model.

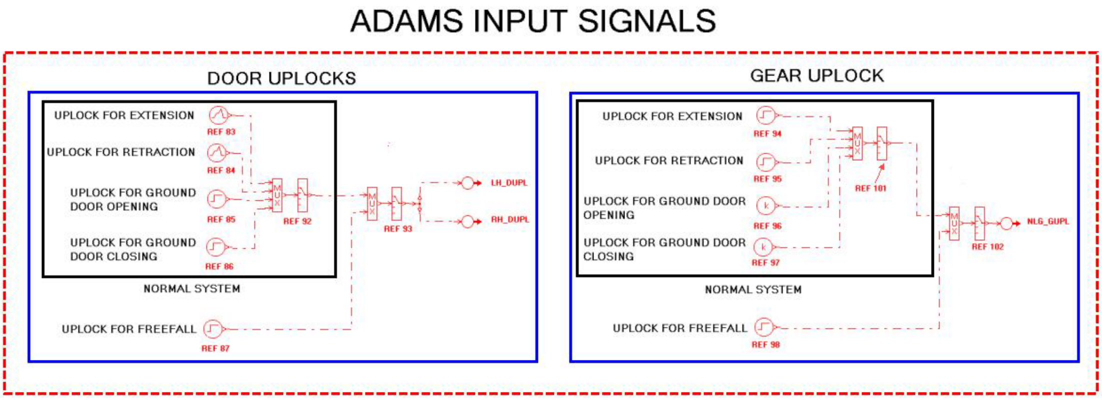


Fig. 3.22. Adams inputs from AMESim [13]

Figure 3.22 shows some of the inputs that ADAMS is going to received as for example the doors and gears up-lock, which "Up-lock signals are generated in AMESim as Boolean values (1 for up-lock engaged and 0 for disengaged), and they are sent to ADAMS, where they must be converted into appropriate forces and torques that act on the up-lock mechanism to engage or disengage it" [13]. During the mentioned section a more detailed explanation exists where the configuration of ADAMS and AMESim is explained, but it is out of the scope here.

One of the advantages of doing a co simulation like the one that has been explained is that in order to do the simulation is just running the model in ADAMS as a classic mechanical model while AMESim is open and running in background. And once the configuration of the interface between both is defined, there is no need to redo it even if some changes are done in some of the programs, because they actualize by their own.

Now in the following images are shown some of the results obtained by Gabriele Bernardini during the co-simulation between ADAMS and AMESim and the results of a physical test [13]. As it can be seen both results are so similar so it can be state that the virtual test was so close to the reality, so the model was properly defined and the use of co-simulation can be very beneficial in the aerospace industry between others.

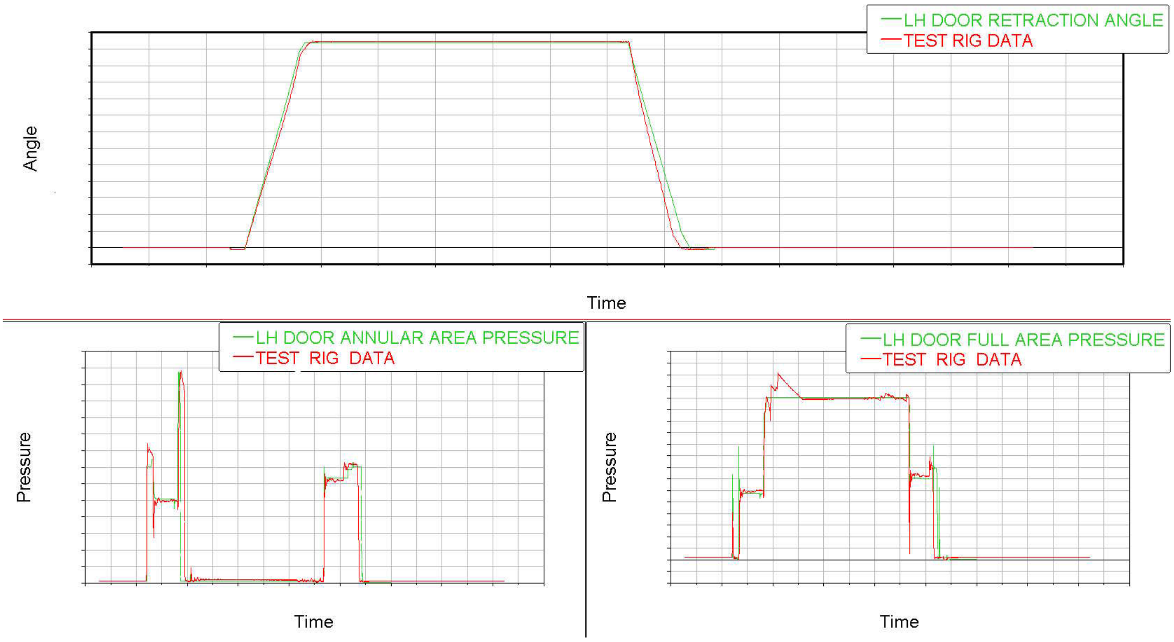


Fig. 3.23. LH door retraction angle and pressures in door actuator chambers for normal extension [13]

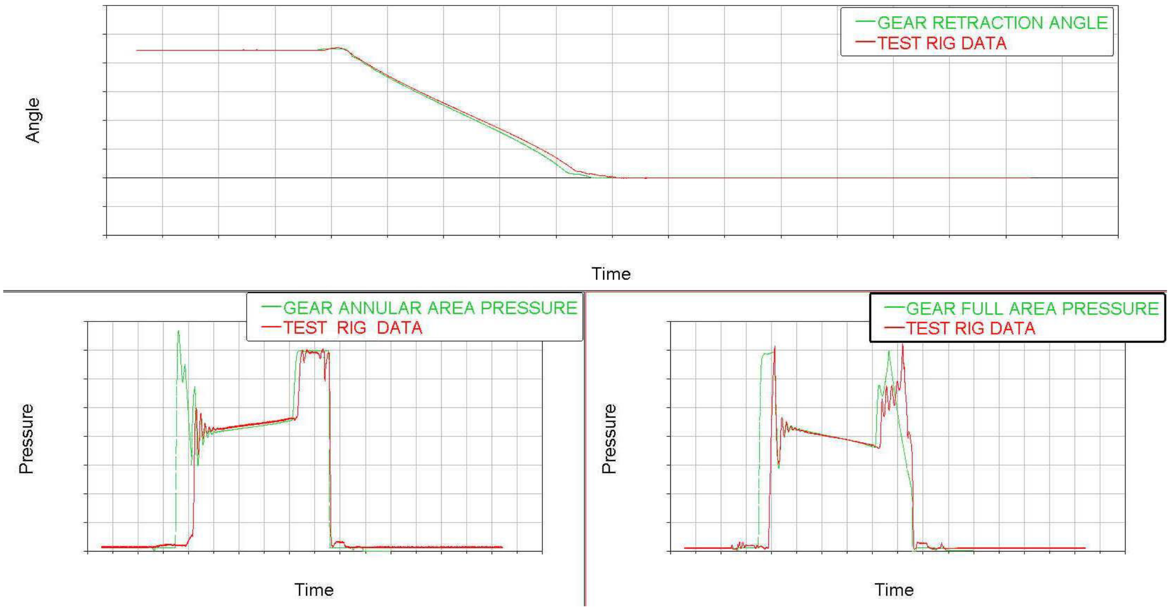


Fig. 3.24. Gear retraction angle and pressures in gear retraction actuator chambers for normal extension [13]

3.4. Altair HyperWorks Applications

During the research process, another interesting software has been found. The program belongs to Altair Engineering and is called Altair HyperWorks [14]. This is a complete CAE program which is composed by different modules as ADAMS, some of them are:

- HyperMesh
- SimLab
- AcuSolve
- WinProp
- HyperGraph
- Virtual Wind Tunnel
- HyperStudy and HyperView
- HyperCrash
- MotionSolve
- nanoFluidX
- OptiStruct
- RADIOSS
- InCa3D

This program allows to model the mechanism and do a complete linear or non-linear analysis while optimize the structure. But the main difference with ADAMS is that it works with fluid mechanics analysis, electromagnetic devices can be included in the model and thermal analysis can be done. But as ADAMS multi-body simulation is one of the main use. [15]

3.4.1. Applications of Advanced Composite Simulation and Design Optimization

In the website of the company [14] there is a Resource Library in which a lot of technical papers and customers stories can be found. In that sector there has been a paper that has called my attention and it is very interested for the goal of this thesis. The technical paper is "Applications of Advanced Composite Simulation and Design Optimization" which autors are Ming Zhou, Sam Patten, Martin Kemp, Robert Yancey, Erwan Mestres and Jean-Baptiste Mouillet [16].

In this paper two cases are studied, the first one is a bird strike simulation computed with RADIOSS and DIGIMAT while the second one is about an airplane wing optimization with OptiStruct. But firstly there is a brief introduction where both problems are presented and it can be seen how the main goal is to study the behaviour of the composite material with simulation because composite material are more complex than metals as "Composite damage mechanisms are also varied and can include delamination, fiber breakage, matrix failure or a combination of all of these" [16].

Focusing first in the bird strike simulation, "RADIOSS is an explicit and implicit finite-element solver technology that simulates impact, mechanical, structural, fluid and fluid-structure interaction phenomena, taking into account nonlinear material, for quasi-static and dynamic loading events"[16]. While "DIGIMAT is a micromechanical modeling code that links with finite element analysis to determine the stress, strain and damage at the constituent level" [16].

That is how the two tools are described in the paper and the main goal is to study and understand the behaviour of an underbelly fairing subjected to bird strike. So the deformation of the material and the damage suffered are the main parameters that need to be analyzed.

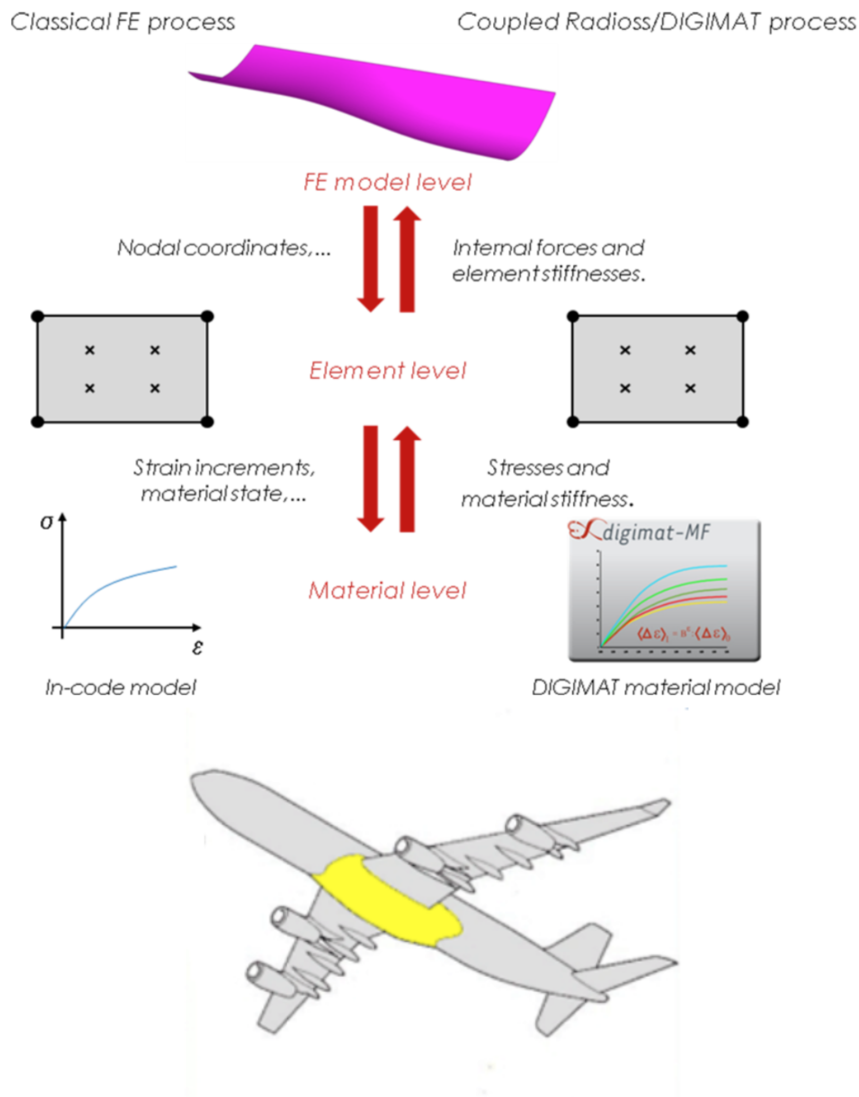


Fig. 3.25. Underbelly fairing and interaction between programs [16]

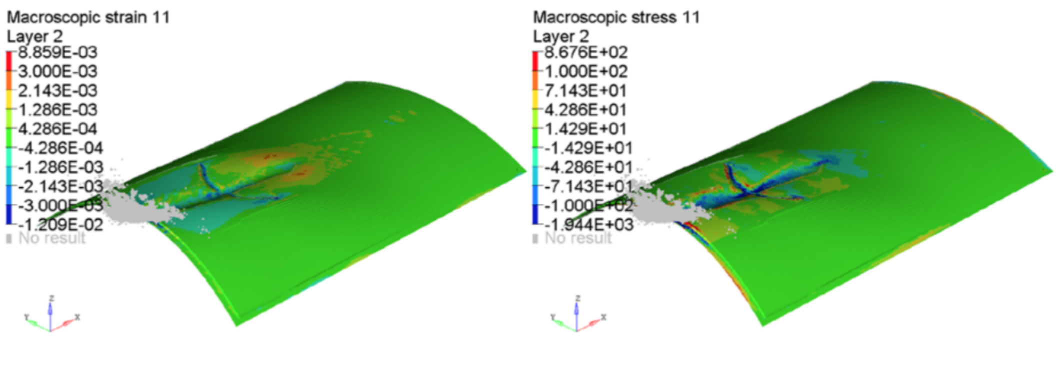
The previous image 3.25 shows the underbelly fairing that is going to be analyzed and the interaction process between RADIOSS and DIGIMAT. But another program was also used in the process, HyperMesh, in order to create the mesh for the piece.

The properties of the materials that have been used are displayed in the following table and they have been taken from Kueh and Pellegrino [17]. With those properties DIGIMAT has developed the material model to use during the analysis.

Property	Matrix (M18)	Fiber (T300)
Density	1160 kg/m^3	1760 kg/m^3
Longitudinal Young's Modulus (E11)	3500 MPa	233000 MPa
Longitudinal Poisson's Ratio (ν11)	0.38	0.2
Transverse Young's Modulus (E22)	3500 MPa	23100 MPa
Transverse Poisson's Ratio (ν22)	0.38	0.2
Transverse Shear Modulus		8963 MPa
Ultimate tensile Strength		1990 MPa
Ultimate compressive Strength		1990 MPa
Ultimate tensile strain	0.037	
Ultimate compressive strain	0.0481	

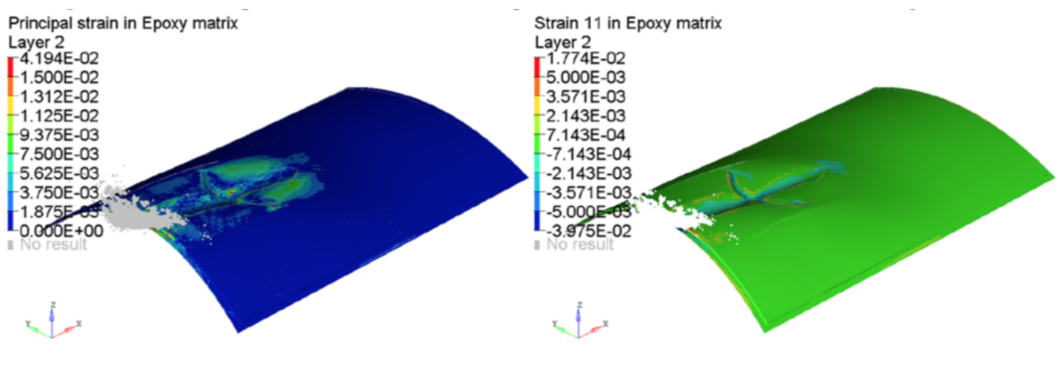
Fig. 3.26. Material properties [16]

Before showing the results obtained during the analysis is interesting to know that "Altair's RADIOSS finite element solver has a validated bird model based on Smooth Particle Hydrodynamics (SPH) theory ... The model has been validated with extensive test data. The model was run in RADIOSS with stress, strain, kinetic energy, velocity, deceleration information and deformation limits predicted" [16].



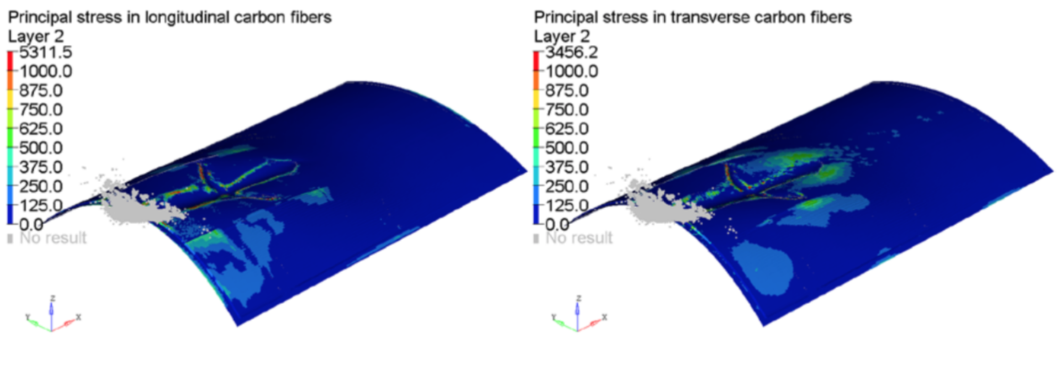
ε_{11} (X-Direction) Macroscopic Strain **σ_{11} (X-Direction) Macroscopic Stress**

Fig. 3.27. Macroscopic stress and strain in composite structure under bird strike loading condition [16]



ε_{11} (X-direction) Strain in Matrix **First Principal Strain in Matrix**

Fig. 3.28. Computed strains in M18 Epoxy Matrix [16]



First Principal Strain in Longitudinal (0°) Fibers **First Principal Strain in Transverse (90°) Fibers**

Fig. 3.29. Computed First Principal Strains in Longitudinal and Transverse Fibers [16]

Previous figures show the macroscopic stress and strain and detailed data for the isotropic matrix and the transversely isotropic fibers. But the microscopic failure of the material needs to be consider and in order to do failure indicators are going to be introduce so DIGIMAT can create a more accurate model, which can be seen in Figure 3.30 where a greater value than 1 (in red) means that the layer fails.

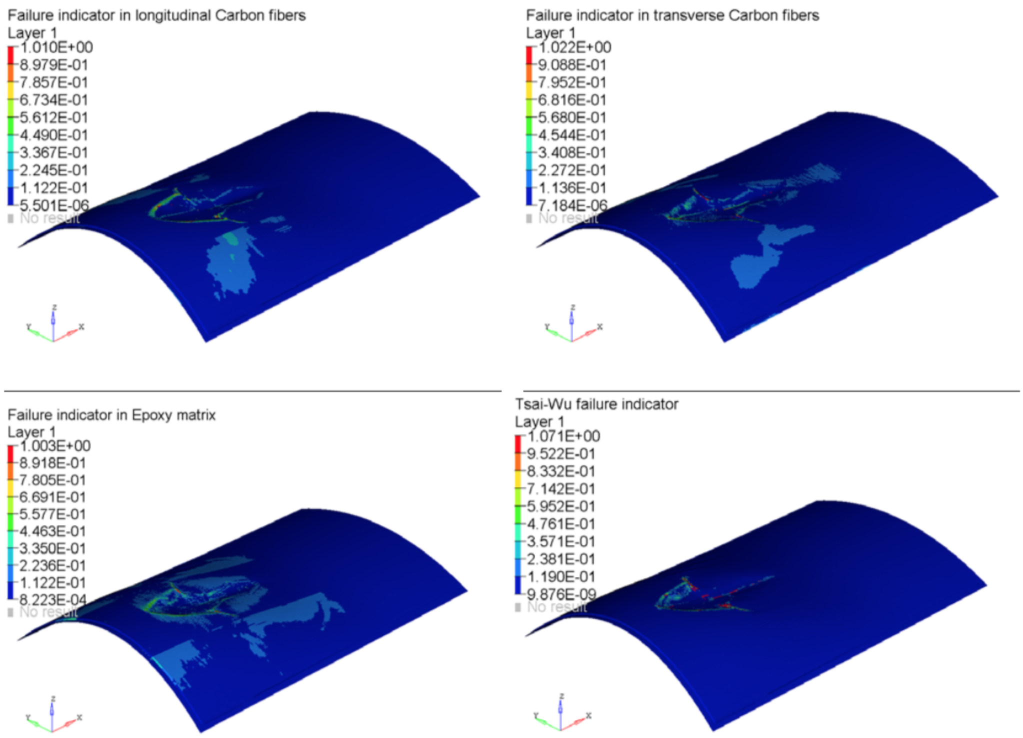


Fig. 3.30. Failure indicators in Carbon fibers, in Epoxy matrix phase and at macroscopic level [16]

After that, the Airplane wing optimization study is presented. In which first a design process commonly used in the design of composite materials is explained, it is called the "Three-Phase", it has been the process used during this study.

During the "Phase I: Concept Design - Free-Size Optimization" [16] different distribution of the thickness for the fiber and its orientation are tested in order to find the most suitable configuration. But it is important to remark that "Ply orientation available are 0, +45/-45, 90 plies, with leading edge as a reference" [16].

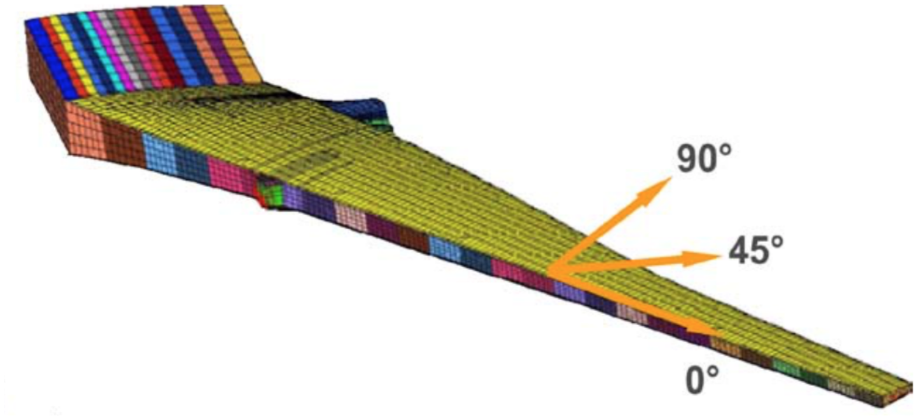


Fig. 3.31. Wing model created with composite [16]

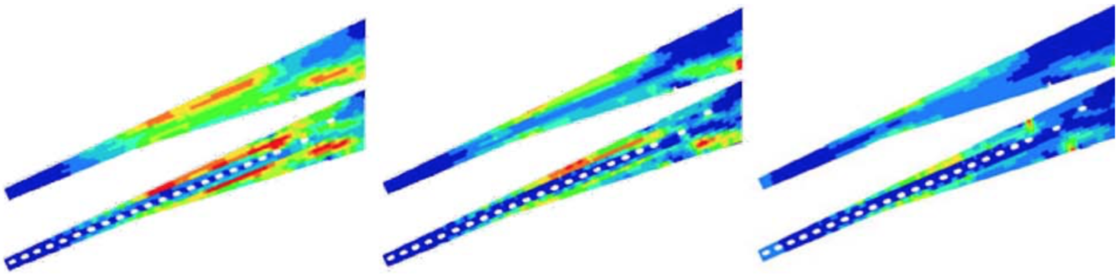


Fig. 3.32. Thickness distribution (0 left, +45/-45 center, 90 right) [16]

"At the end of the Free Element Sizing optimization, OptiStruct automatically generates ply shapes based upon the optimization results" [16]. That can be seen in the figure 3.33 where the distribution of ply shapes have been modified by the program. These results are the final ones for the first phase and are going to be the inputs for the second phase.

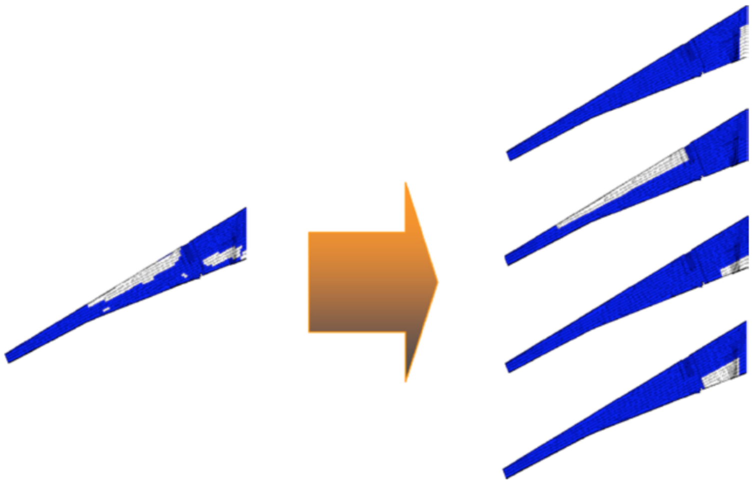


Fig. 3.33. Final ply shaped modified by HyperMesh [16]

"Phase II: Design Fine Turning - Ply-Bundle Size Optimization" [16] is in charge of consider constraints such as strength and stability in order to compute the best thickness contour and the number of plies that need to be created for the desired piece of study, that in this case is the wing. The thickness contour is shown in the Figure 3.34:

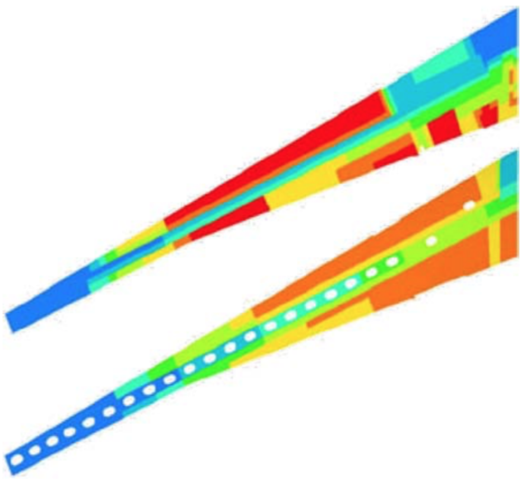


Fig. 3.34. Thickness contour from optimization process [16]

Finally the last phase is "Phase III: Ply-Book Details - Ply Stacking Sequence Optimization" [16] where as its own name indicate the stacking optimization is the main goal of this part, which is part of the latest design details where the requirements need to be maintained.

The optimize ply sequence and a more detail view of the plies can be seen in the following figures. In order to get the second figure "a utility is available in HyperMesh to show solid view for visualization purpose. The utility allows thickness scaling and also applies the element & laminate shell reference plane offset" [16].

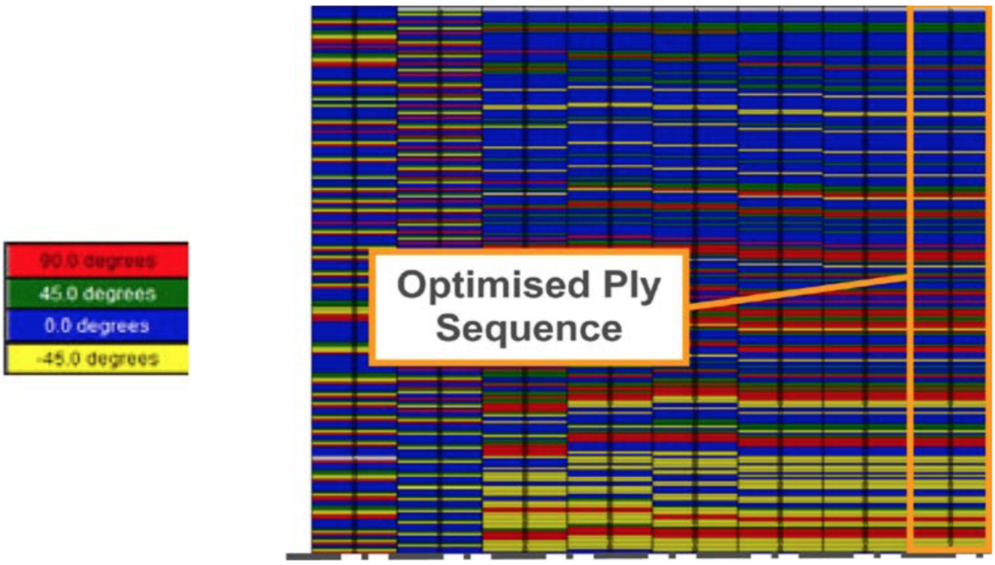


Fig. 3.35. Stacking Optimization [16]

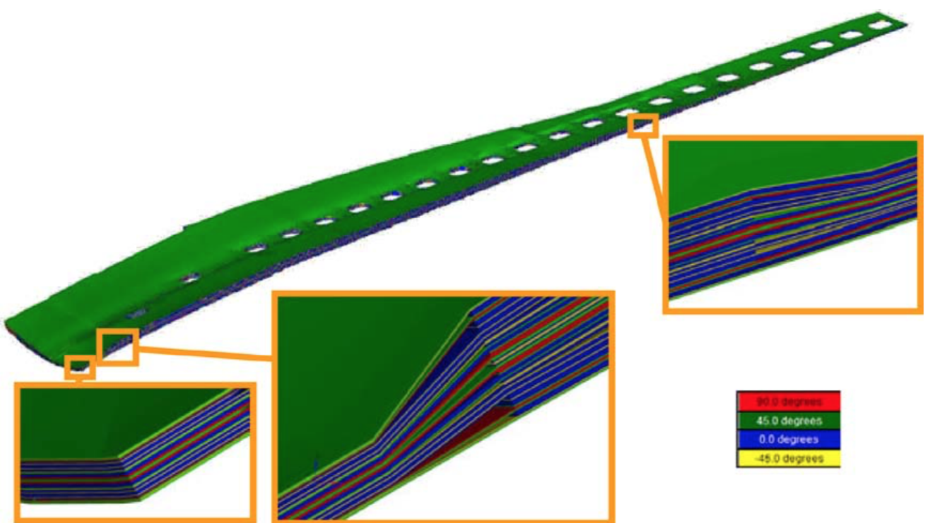


Fig. 3.36. Visualization of Plies (Thickness x5) [16]

After that two applications, there is an extra section in the paper which is dedicated to "Application of Altair composite design optimization process to aero-structure composite component development at Bombardier" [16]. Which I have found very interesting since it show how an actual and important aeronautical company such as Bombardier uses VT in its daily work. Which gives us the opportunity to see how more and more companies are relying in this technology.

The integration of the process created by Altair in such company is illustrated in the Figure 3.37:

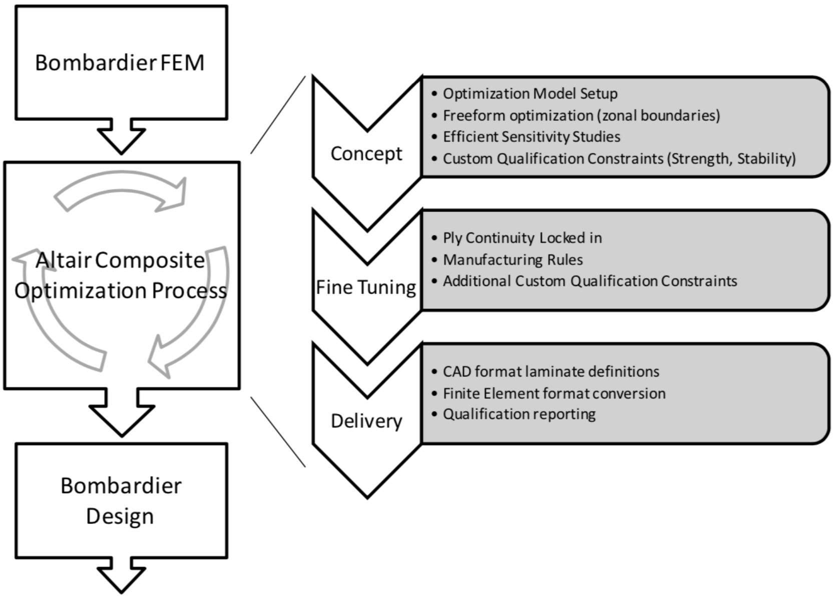


Fig. 3.37. Method of integration of Altair's Process in Bombardier) [16]

It can be seen how the data from the FEM model is the input data for the Composite Optimization Process of Altair, for which the different steps are summarize in the diagram. For this particular case "The optimization problems were typically defined to minimize mass subject to stiffness, allowable stresses and stability criteria" [16].

Finally, to sump up this large technical paper it is said "The composite optimization process was applied successfully in a real world aerospace design environment allowing efficient exploration of designs and delivering weight saving potential for a range of components and systems" [16]. What they have studied is crucial for this thesis and in the paper has also highlighted some of the major advantages, if anyone is more interested.

3.4.2. Altair’s Products and Partners Offering Assist Commercial Vehicles Seat Manufacturer to Enhance its Development Process

In this paper a real history of one of the clients of Altair is written. The company is a seat manufacturer for trucks and bus, and is composed by ISRINGHAUSEN brand, which is part of the AUNDE Group [18].

Fig. 3.38. Design of a seat of ISRINGHAUSEN [18]

The main goal of this company is the same that was said at the beginning of the thesis, reduce the pressure that the workers have to develop new designs in shorter time, for that, the whole process should be faster and less expensive. They have the same global vision, "To meet these expectations, they need simulation tools that enable them to develop virtual models that behave almost exactly like a physical prototype and that can be manufactured as designed. The effort of prototype testing should ideally be reduced to the validation of the simulation results" [18].

Obviously, all the seats are not going to have the same requirements because each client would specify their desired ones. So the possibility of changing parameters faster and without a huge increase in cost is a necessity nowadays.

Altair has the solution to that, their clients have access to the tools availables in Altair Partner Alliance (APA), which is constantly adding new software to it. With that advantage "Customers use floating licenses to access a suite of third-party applications from Altair and HyperWorks partners, that can be employed with the same units used to invoke HyperWorks software" [18].

In this case it is said that "Isringhausen today accesses more than ten different APA products and covers a major part of the CAE process with those tools" [18]. Thanks to that they can fulfill the requirements of the clients at the same time of fulfilling the safety regulations.

"Next to structural analysis, the engineers have to cover the areas optimization, multibody simulation, NVH analysis, durability, and safety. Additionally, they have to consider manufacturing aspects of the different components depending on the material they are made of" [18].

They also use Altair HyperMesh, first CAD department would create the design and that design is going to be submitted to a simulation and once the results of the simulation are obtained using HyperMesh would create a improved mesh for the piece taking into account the results obtained previously. Apart from that program it also "uses OptiStruct, RADIOSS, MotionSolve, plus one third party solver" [18].

It is also mentioned another programs that uses such as Moldex3D (Figure 3.39) in order to "simulate the injection molding plastic parts" to "ensure that the parts are designed in a way that will not cause problems in the manufacturing process" [18]. Or "DesignLife is applied for fatigue analysis, to study durability issues of components and complete seat structures under specified loads and for product life cycle requirements" [18].

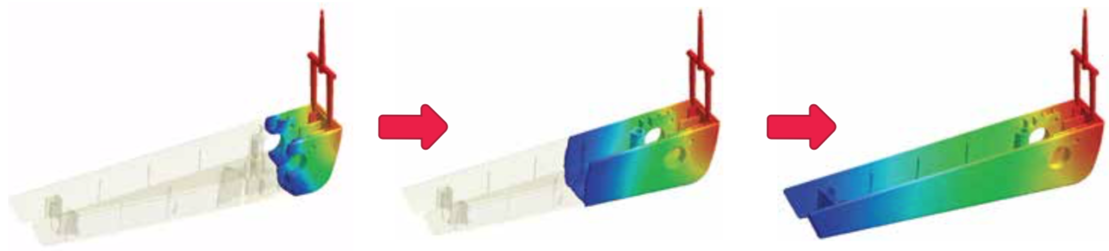


Fig. 3.39. Molding injection in Moldex3D [18]

Finally, in the conclusion section it is explained how they have obtained a big reduction in time and cost and how the company is very satisfied with the results obtained and the services that APA offers.

3.5. Final program chosen: ADAMS

After all that research, in this thesis the chosen program has been ADAMS from the company MSC.

ADAMS is one of the most worldwide used multibody dynamic simulation software. With this tool many mechanism and prototypes can be easily created and enables us to study the dynamism of movable parts, applying loads and forces.

The software gives a complete analysis of the mechanical model and the study can be static, kinematic, quasi-static or dynamic. As it can be see in the official product Data sheet of the program [19].

It has five main business value which are:

- "Improve Engineering Productivity"
- "Accelerate Time-To-Market"
- "Reduce Manufacturing Costs"

- "Achieve Lower Warranty Costs"

- "Drive Innovation"

Those values are mainly the ones that have been discussed in the introduction of the thesis. The advantages are the reduction in time and cost and the ability to simulate several design concepts with variations in shorter time. And due to that the performance and life time cycle are better predicted so that makes a reduction in warranty costs. Another advantage of this software is that flexible components can be integrated in the models so the deformation and the stresses suffered in the bodies can also be known. In the Figure 3.40 it can be seen a model of a landing gear created by Gabriele Bernardini in his thesis (Figure 2.13 in his thesis) [13].

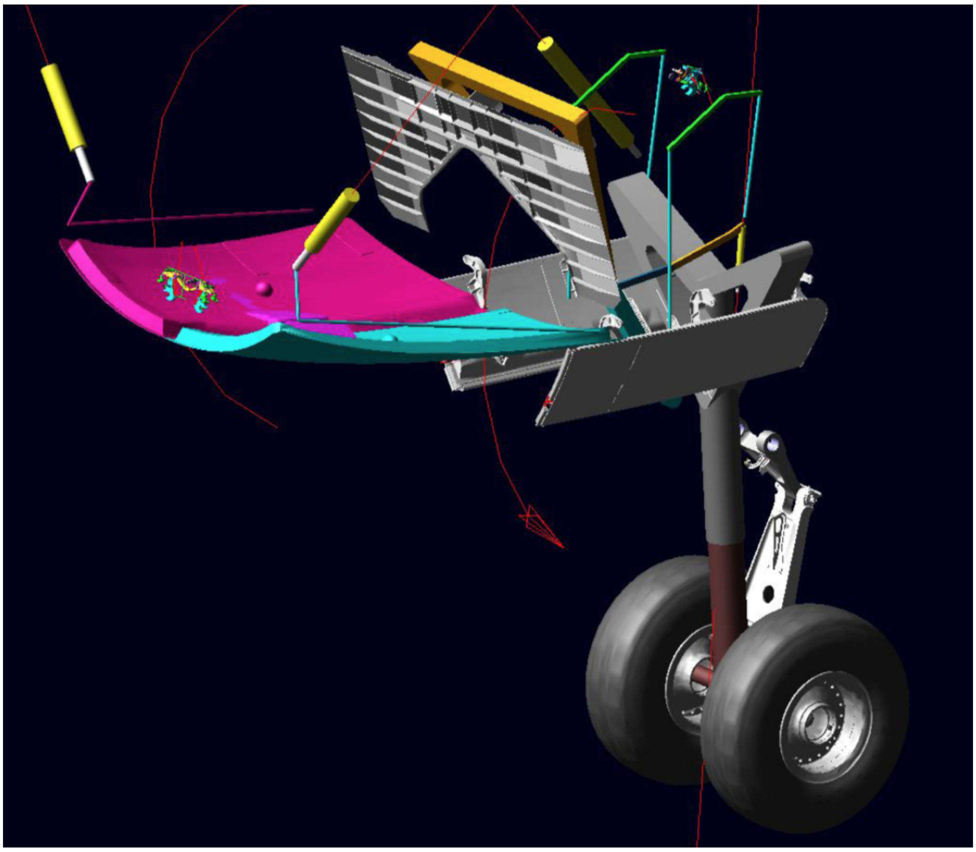


Fig. 3.40. Example of Nose Landing gear created in ADAMS

This program has multiple utilities because it has different modules that can be purchased separately. A briefly list is given below but more information about each one can be found in the official website of MSC.

- Adams/View
- Adams/Solver
- Adams/PostProcessor
- Adams/Flex
- Adams/ViewFlex
- Adams/Durability
- Adams/Vibration
- Adams/Controls
- Adams/Exchange
- Adams/Tire FTire
- Adams/Insight
- Adams/Car and Adams/Car Real Time
- Adams 3D Road
- Adams/Machinery
- Adams/Mechatronics
- Adams Tire Handling
- Adams/Aircraft
- Adams/Rail

During this thesis the modules that have been used have been Adams/view, Adams/-Solver, Adams/PostProcessor, Adams/Flex and Adams/ViewFlex. These modules would be explained in the subchapter 4.2 where the procedure followed during the creation of the piece in ADAMS is described.

As it can be seen this huge variety of modules give the opportunity to have all the necessary tools to create and analyzed all types of prototypes and mechanisms. Now that the advantages of ADAMS are clear and papers of projects done with others software have been analyzed to see its advantages and differences between them, it is clear that ADAMS offers all the utilities necessary not only for the aerospace industry but also for other sectors.

4. SIMULATION OF THE PIECE OF STUDY AND RESULTS

The main goal of this thesis was to study the viability of virtual testing in the industry. To do so the first step was research as it can be seen in the previous chapter in which a lot of technical papers have been discussed in order to know the current situation of this tool in the actuality. But now, in this chapter it is shown the contact with the program ADAMS.

In order to start using this program, the piece of study is the gravel deflector of the nose landing gear of the aircraft C295. This was also mentioned in the first chapter of the thesis. The first step has been to create a simplified model composed by bars and links with just one spring actuating on the system and later two springs would be considered. In the following figures, the important parts of the gravel deflector are shown and the pieces enumerated are the ones that are going to be simplified by bars.

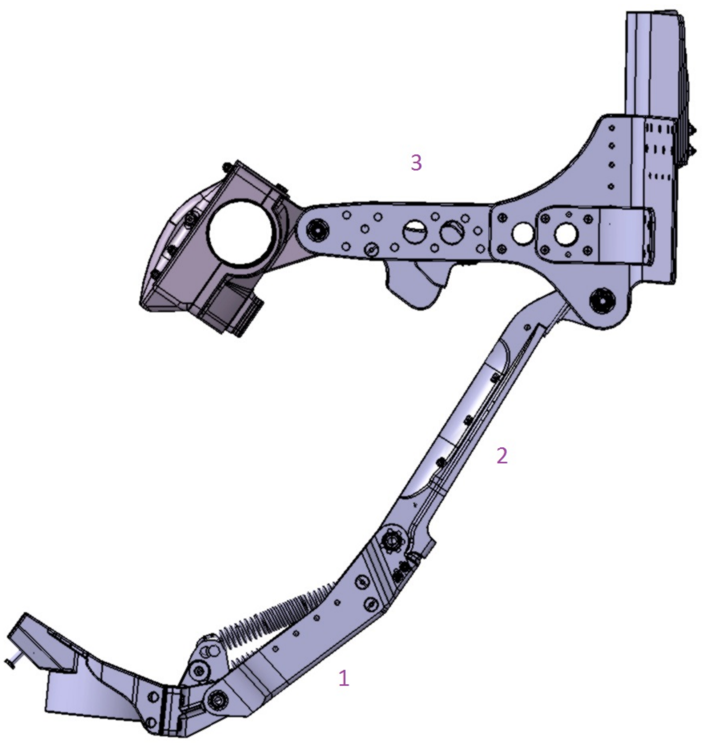


Fig. 4.1. Gravel deflector of the aircraft C295

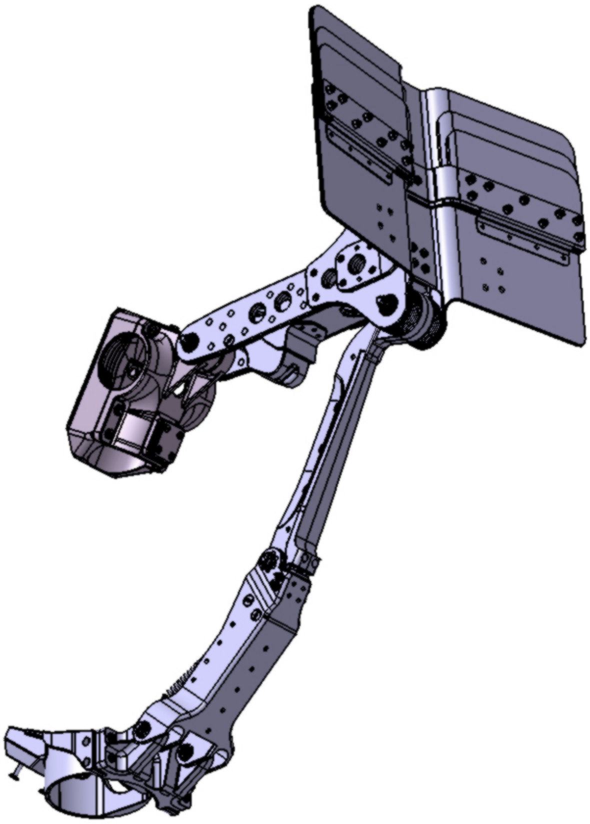


Fig. 4.2. Gravel deflector of the aircraft C295

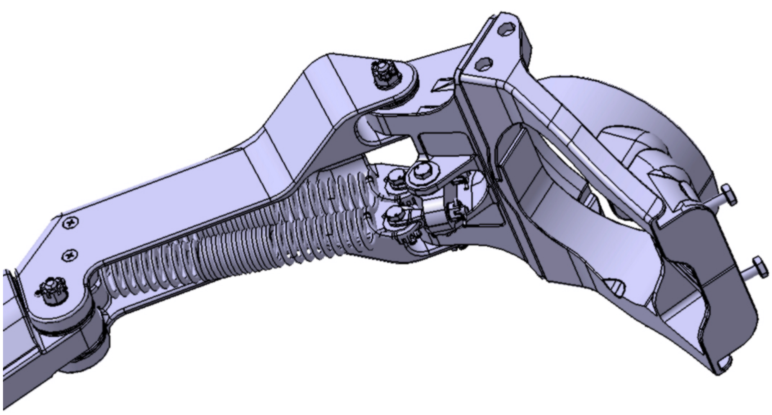


Fig. 4.3. View of the applicated springs

Once the simplified structure was clear, the most important parameter right now to obtain the equilibrium is the spring, because without it, the structure would fall due to the effect of the gravity. So the key factor is the preload that the spring needs to have. The springs can be visualized better in Figure 4.3 of the structure.

4.1. Analytic Study of the mechanics

An analytic study has been done in which the unknowns of the system are: Preload (1 or 2 depending on the number of springs acting on the system), vertical reactions on A and D and horizontal reactions on A and D. Figure 4.4 and 4.5 show the forces that have to be taken into account on the system when one spring is acting and the declared distances that are going to be used during the analytic analysis. The distances are with respect to x (horizontal distance) and z (vertical distance) because that is the plane of reference that has been selected in ADAMS for the model.

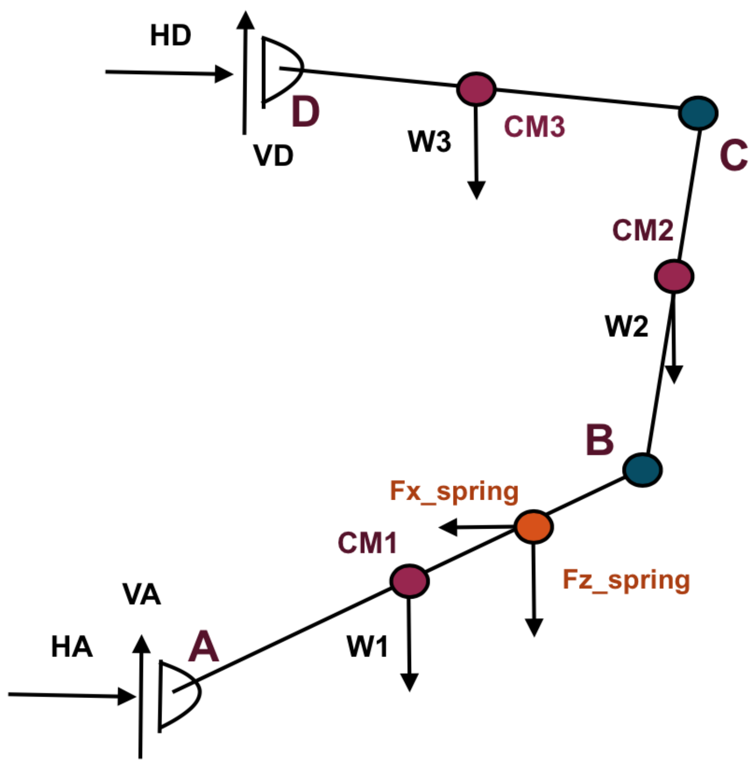


Fig. 4.4. Forces acting in the system with one spring

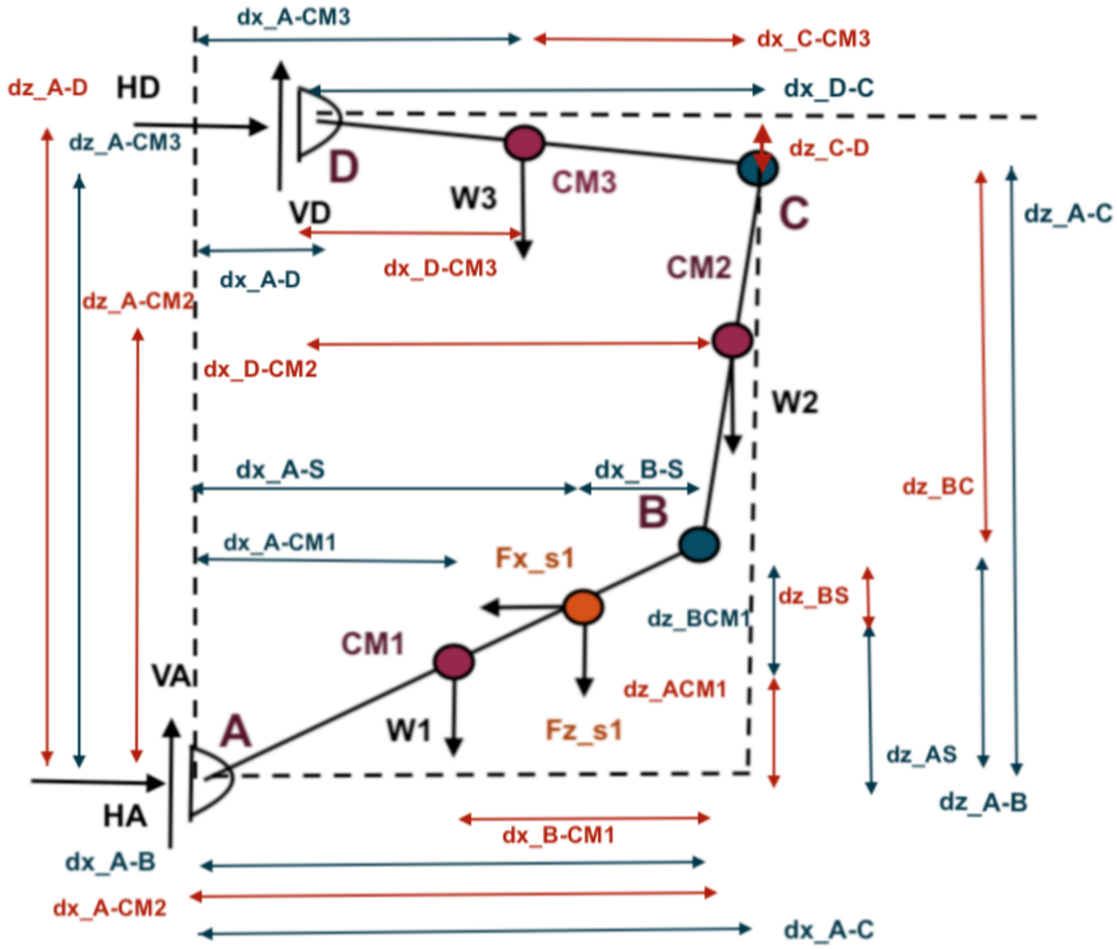


Fig. 4.5. Declared distances with one spring acting

So to get the unknowns of the system, as we are interested in having the system in equilibrium, the following equations need to be fulfilled:

$$F_x = H_A + H_D - Fx_{spring} = 0 \tag{4.1}$$

$$F_z = V_A + V_D - Fz_{spring} - W_1 - W_2 - W_3 = 0 \tag{4.2}$$

$$\begin{aligned} \sum M_A = {} & W_1 \cdot dx_{ACM1} - Fx_{spring} \cdot dz_{AS} + Fz_{spring} \cdot dx_{AS} \\ & + W_2 \cdot dx_{ACM2} + W_3 \cdot dx_{ACM3} - V_D \cdot dx_{AD} + H_D \cdot dz_{AD} = 0 \end{aligned} \tag{4.3}$$

$$\sum M_B = V_A \cdot dx_{AB} - H_A \cdot dz_{AB} - W_1 \cdot dx_{BCM1} \\ + Fx_{spring} \cdot dz_{BS} - Fz_{spring} \cdot dx_{BS} = 0 \tag{4.4}$$

$$\sum M_C = -W_3 \cdot dx_{CM3C} + V_D \cdot dx_{CD} + H_D \cdot dz_{CD} = 0 \tag{4.5}$$

But one modification needs to be done, a second spring has to be included in the model of study, because the real model works with two springs. The procedure to follow is the same as before but now there is one more unknown so an extra equation is needed, for that the sum of the moments with respect to D are also calculated.

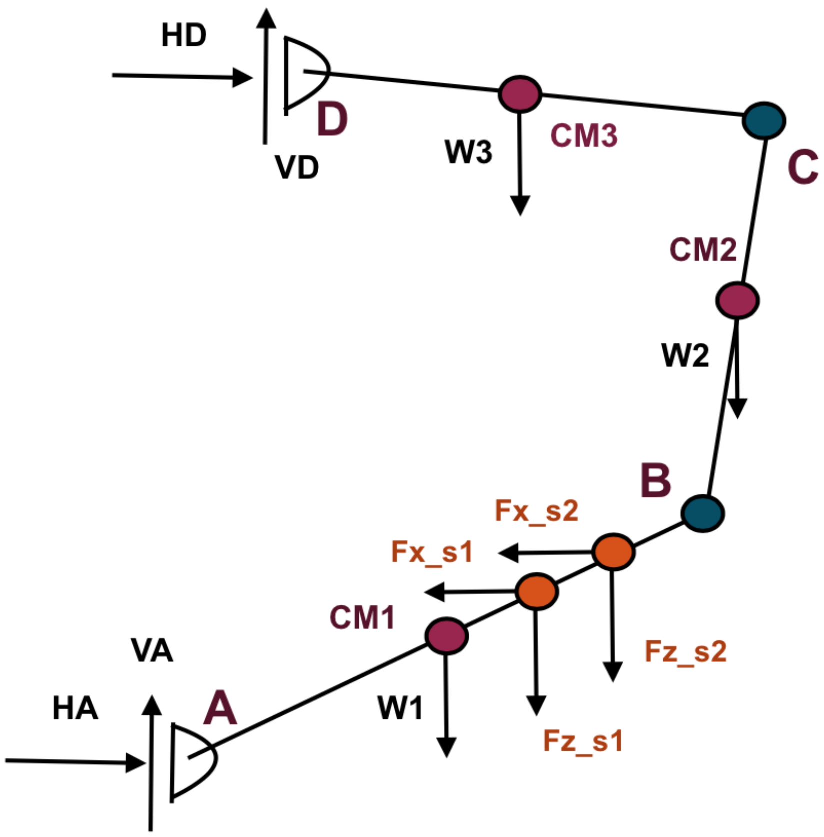


Fig. 4.6. Forces acting in the system with two springs

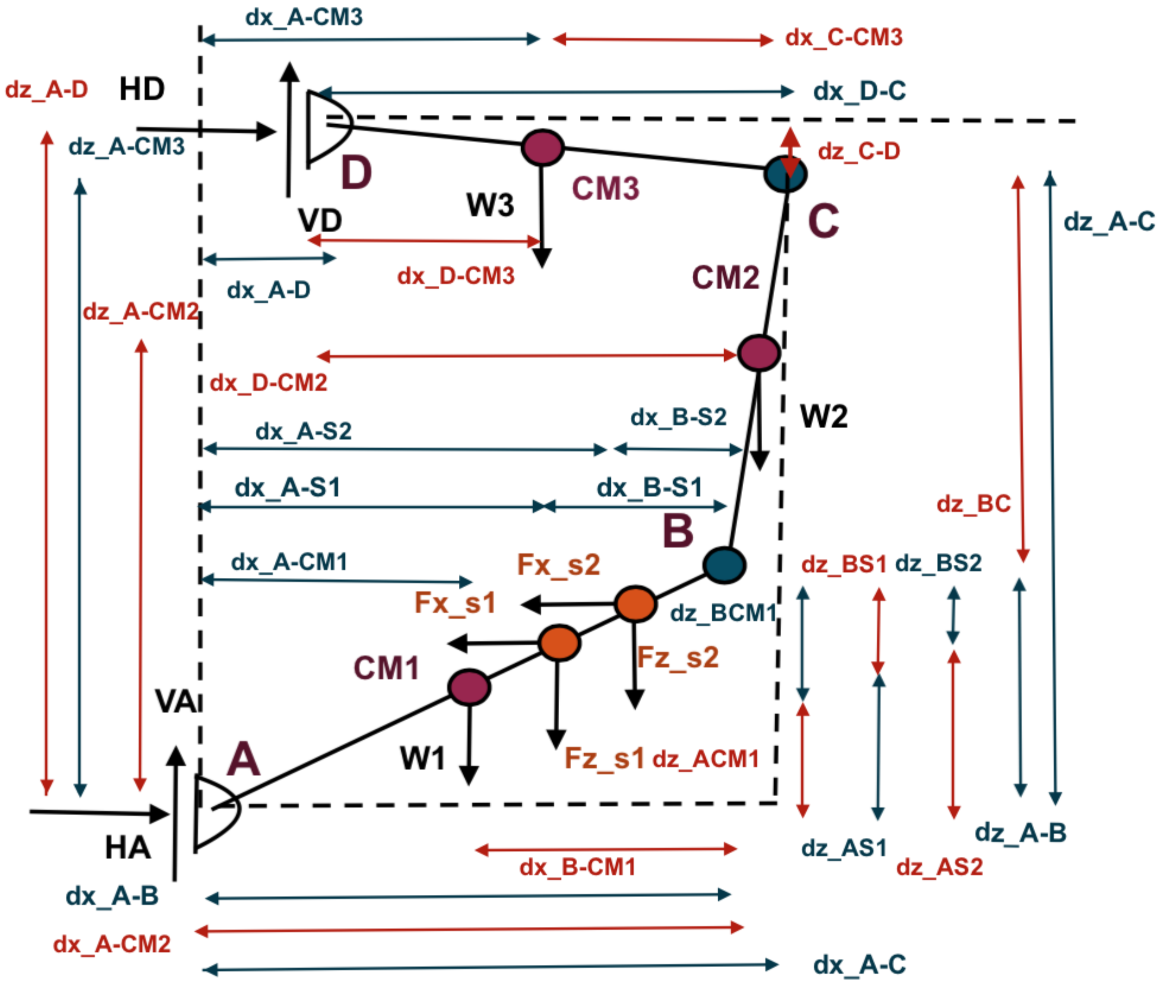


Fig. 4.7. Declared distances with two springs acting

$$F_x = H_A + H_D - Fx_{s1} - Fx_{s2} = 0 \tag{4.6}$$

$$F_z = V_A + V_D - Fz_{s1} - Fz_{s2} - W_1 - W_2 - W_3 = 0 \tag{4.7}$$

$$\begin{aligned} \sum M_A = {} & W_1 \cdot dx_{ACM1} - Fx_{s1} \cdot dz_{AS1} + Fz_{s1} \cdot dx_{AS1} - Fx_{s2} \cdot dz_{AS2} \\ & + Fz_{s2} \cdot dx_{AS2} + W_2 \cdot dx_{ACM2} + W_3 \cdot dx_{ACM3} - V_D \cdot dx_{AD} + H_D \cdot dz_{AD} = 0 \end{aligned} \tag{4.8}$$

$$\sum M_D = W_1 \cdot dx_{DCM1} + W_3 \cdot dx_{DCM3} + W_2 \cdot dx_{DCM2} + V_A \cdot dx_{AD} - H_A \cdot dz_{AD} + Fx_{s1} \cdot dz_{DS1} + Fz_{s1} \cdot dx_{DS1} + Fx_{s2} \cdot dz_{DS2} + Fz_{s2} \cdot dx_{DS2} = 0 \tag{4.9}$$

$$\sum M_B = V_A \cdot dx_{AB} - H_A \cdot dz_{AB} - W_1 \cdot dx_{BCM1} + Fx_{s1} \cdot dz_{BS1} - Fz_{s1} \cdot dx_{BS1} + Fx_{s2} \cdot dz_{BS2} - Fz_{s2} \cdot dx_{BS2} = 0 \tag{4.10}$$

$$\sum M_C = -W_3 \cdot dx_{CM3C} + V_D \cdot dx_{CD} + H_D \cdot dz_{CD} = 0 \tag{4.11}$$

4.2. Creation of the mechanism in ADAMS

The obtained preload with the analytical study for the spring is going to be checked in ADAMS in order to validate if the structure is in equilibrium in the program and see if everything has been defined correctly.

The complete model of that Gravel Deflector has been seen in previous images in CATIA V5 but Landing Gear Department of Airbus Spain has done the complete model in ADAMS too.

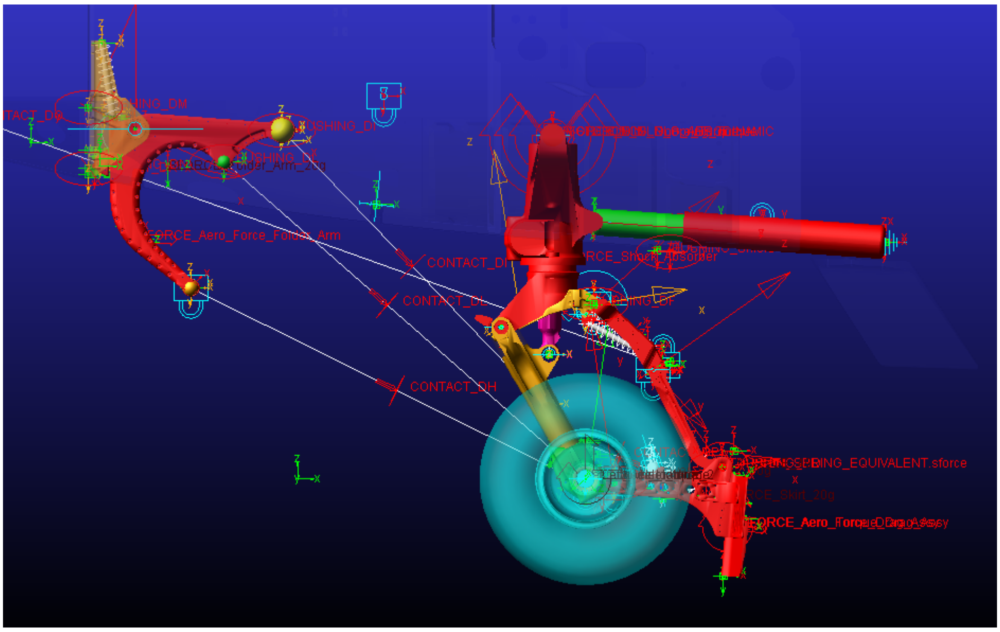


Fig. 4.8. Completed model of the landing gear in ADAMS

So now the model has to be created using ADAMS. Once ADAMS is initialized the main screen looks like:

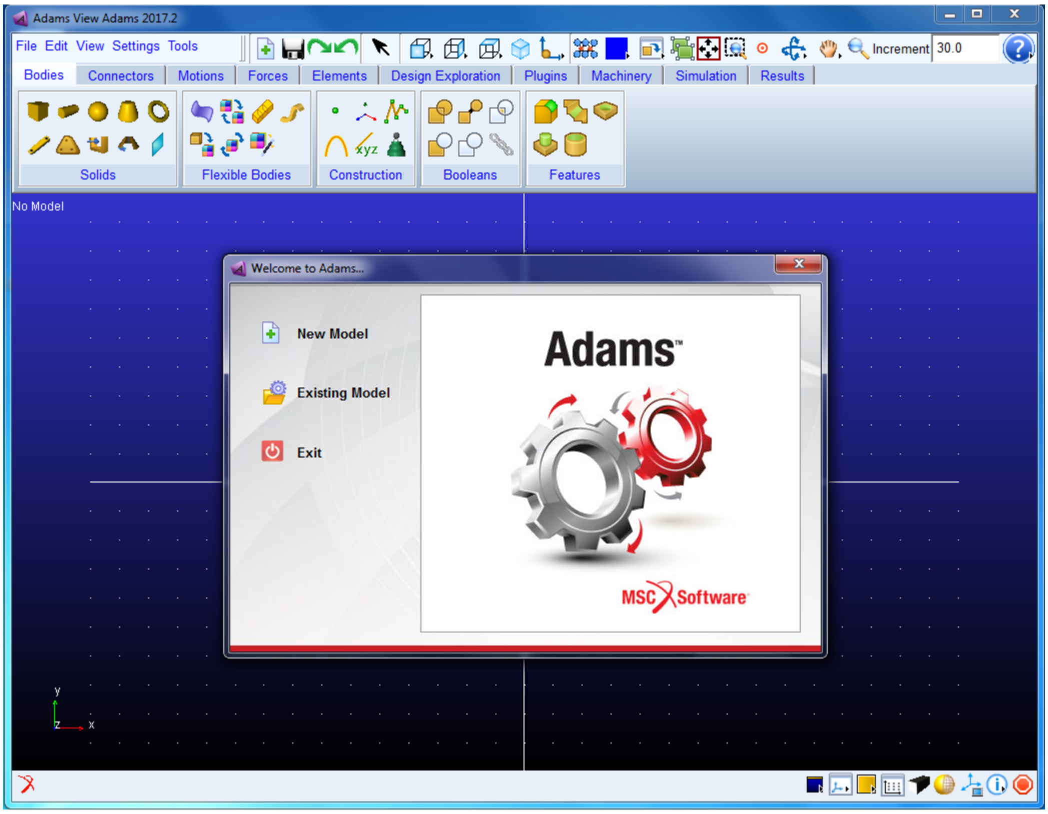


Fig. 4.9. Main screen of ADAMS View 2017.2

Once you select 'New Model' you can start to create the mechanism. It can be seen in Figure 4.9, in the right upper part, how there are different modules of tools to introduce into the model and helps to define the piece. These modules are:

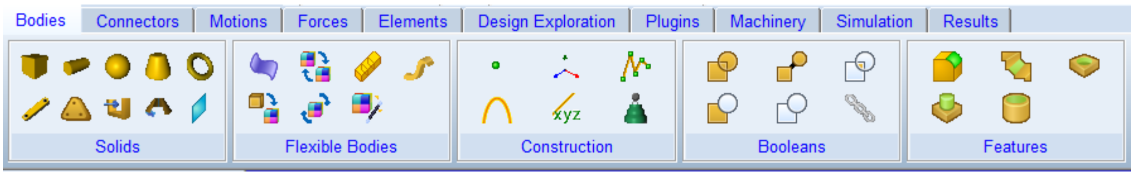


Fig. 4.10. Bodies tools of ADAMS View 2017.2

Fig. 4.11. Connectors tools of ADAMS View 2017.2

Fig. 4.12. Motions tools of ADAMS View 2017.2

Fig. 4.13. Forces tools of ADAMS View 2017.2

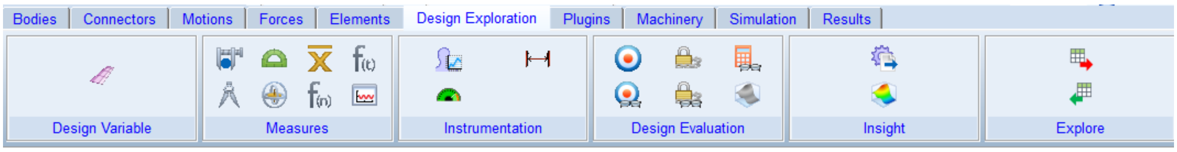


Fig. 4.14. Design Exploration tools of ADAMS View 2017.2

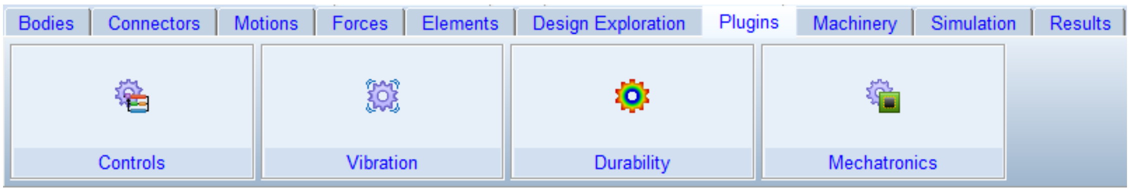


Fig. 4.15. Plugins tools of ADAMS View 2017.2

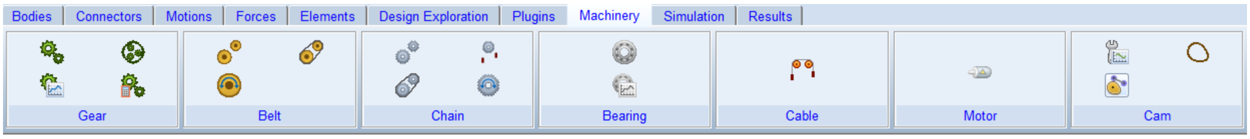


Fig. 4.16. Machinery tools of ADAMS View 2017.2

Fig. 4.17. Simulation tools of ADAMS View 2017.2

Fig. 4.18. Results tools of ADAMS View 2017.2

With the help of these tools, the simplified model has been created. First the points have been created attached to the ground and then the body 'links' is used. Once the links are created the connection between them need to be established in order to define properly the motion of the mechanism.

Link 1, which is called in Adams Part 5, is attached to the ground and is fixed in displacement and can only rotate about it. In its other extreme is joined with the Link 2 (Part 3 in ADAMS) with a revolute joint. Link 2 in also joint with Link 3 (Part 4) with another revolute joint. And finally, Link 3 is also attached to ground as Link 1 was, so it can only rotates about its point of definition.

The next step is to introduce the springs. For that, going to the module Forces, in Flexible Connectors (Figure 4.12), the creation of springs can be selected so the configuration is shown in the next figure:

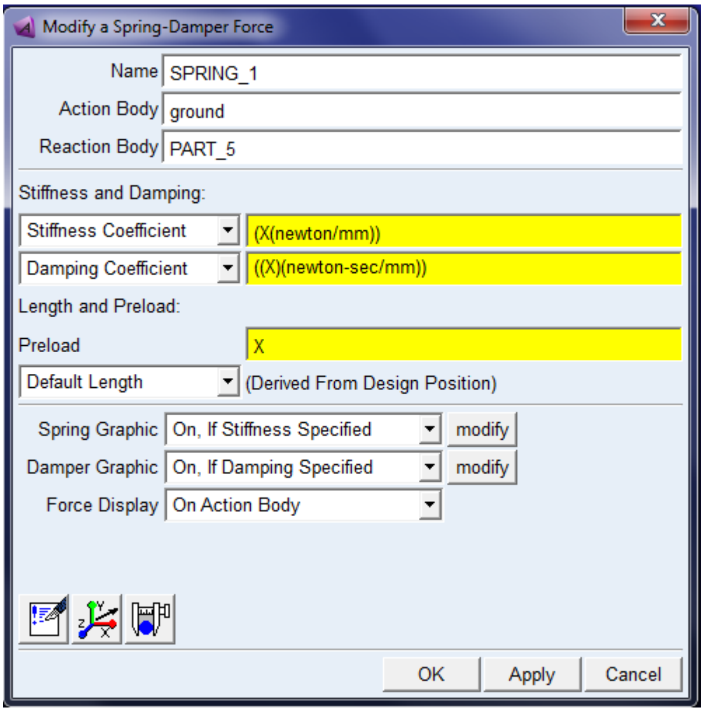


Fig. 4.19. Configuration menu for the spring

Once everything is done, the model looks like the following images:

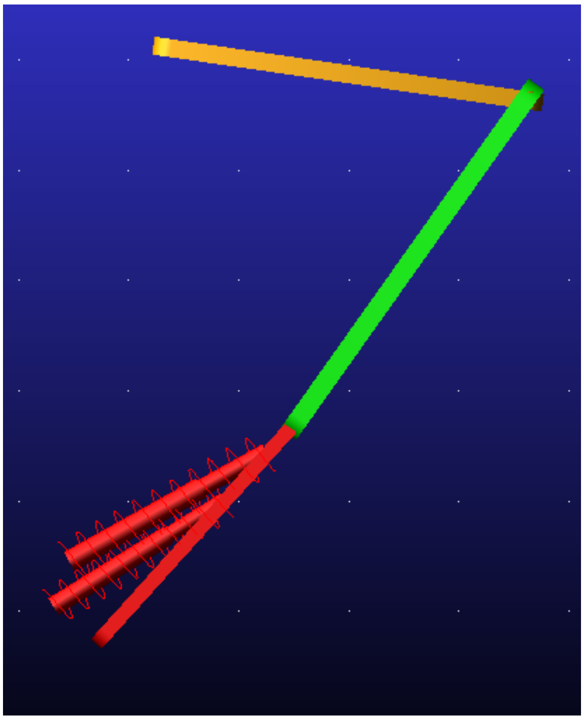


Fig. 4.20. Model created in ADAMS View 2017.2

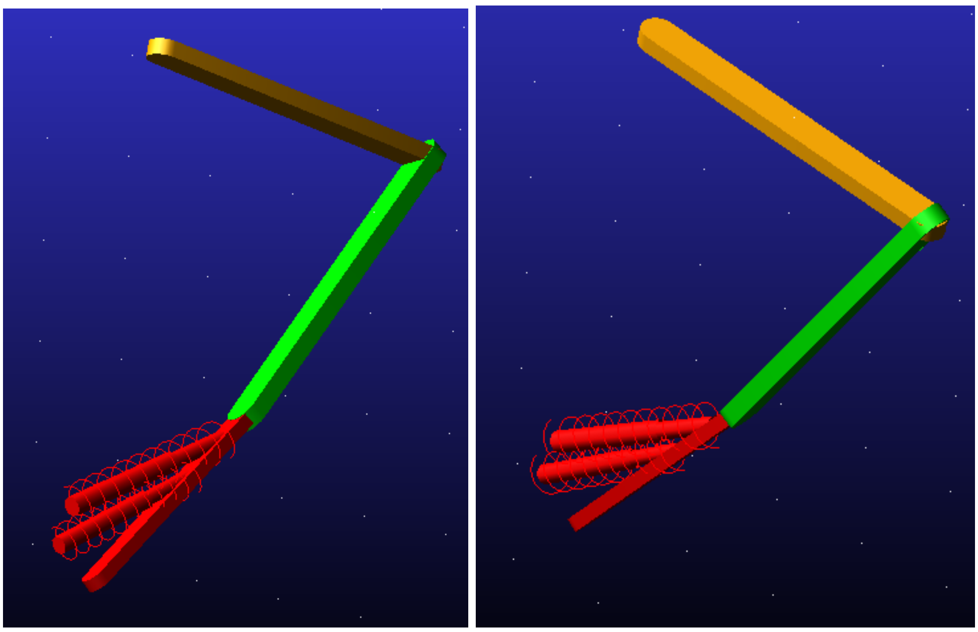


Fig. 4.21. Overview of the model in ADAMS

Once everything is defined, the previous calculated preload is going to be introduced. Here a remarkable data has to be given, in a first step instead of using the real values of the weight of the pieces, the default masses calculated by ADAMS are using as an approximation to check how the model works. And the material used in these first results is steel because is the default one in ADAMS.

W1	W2	W3
7.43 N	18.31 N	14.15 N

Table 4.1. WEIGHTS OF THE LINKS MADE OF STEEL

The results obtained were correctly calculated with an error of 0.5 N in the preload values, and that could be because the distances were rounded so not all the decimals were taken into account during the analytical analysis. So in order to check if the results were valid, the most important parameters were the displacement of the springs and they are shown in the following graphs:

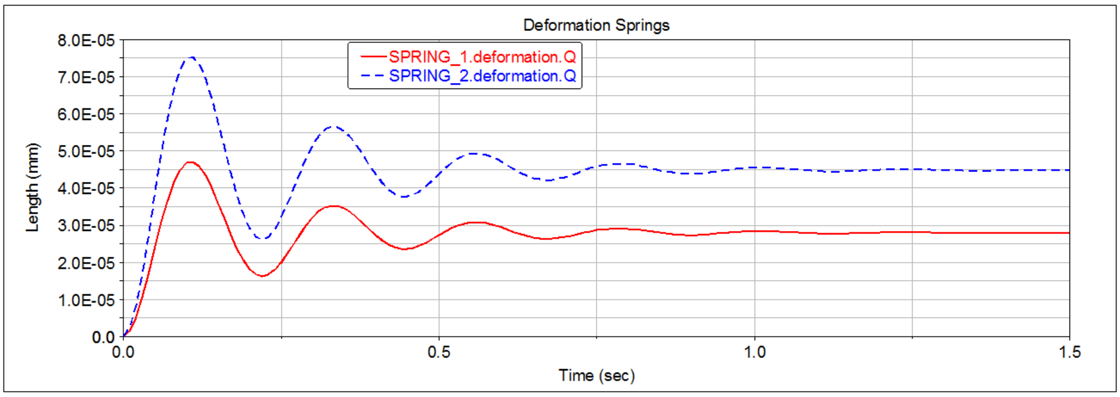


Fig. 4.22. Deformation of the spring in equilibrium with steel

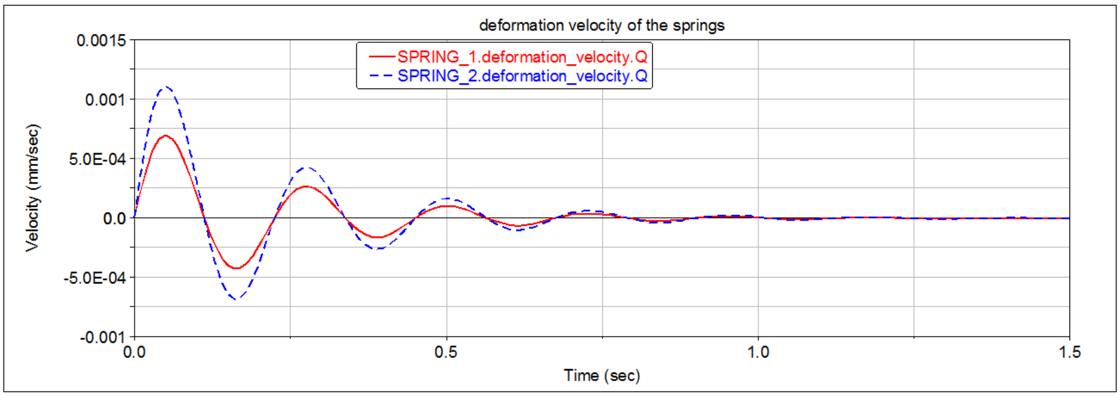


Fig. 4.23. Deformation velocities of the spring in equilibrium with steel

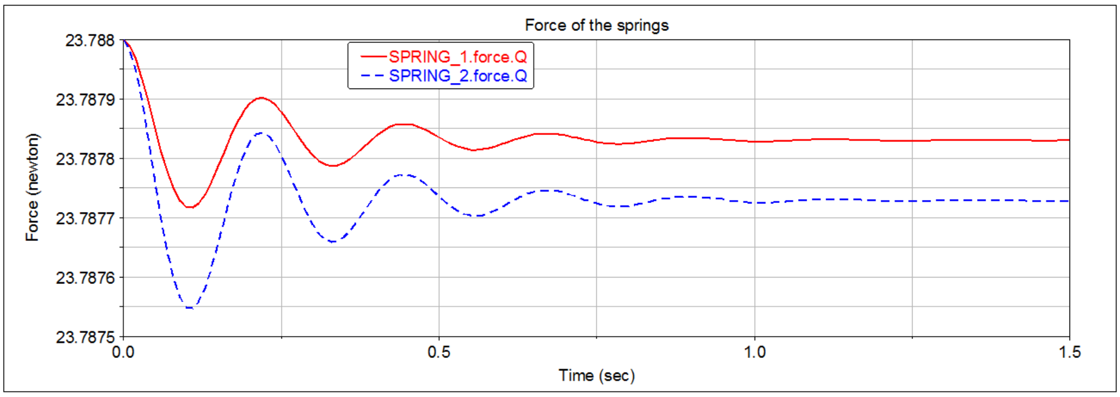


Fig. 4.24. Forces of the springs in equilibrium with steel

As it can be seen the deformations suffered by the springs are so small, of the order of E-05, but also from the graph it can be said that it tends to stabilize with time. Also the velocity is so small and the force remain mostly constant over time.

Also the displacements, velocities and accelerations of the CM of the links can be visualize in ADAMS/PostProcessor:

- Link 1 CM

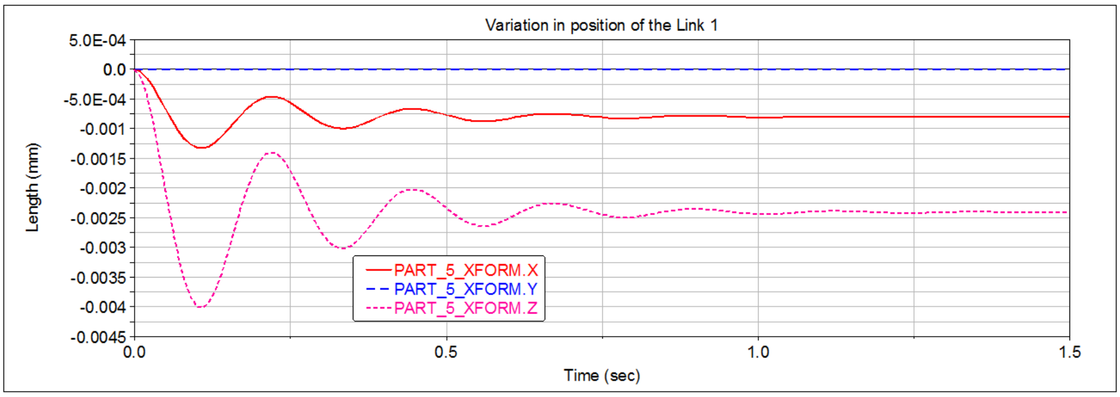


Fig. 4.25. Change in position of CM1 with steel

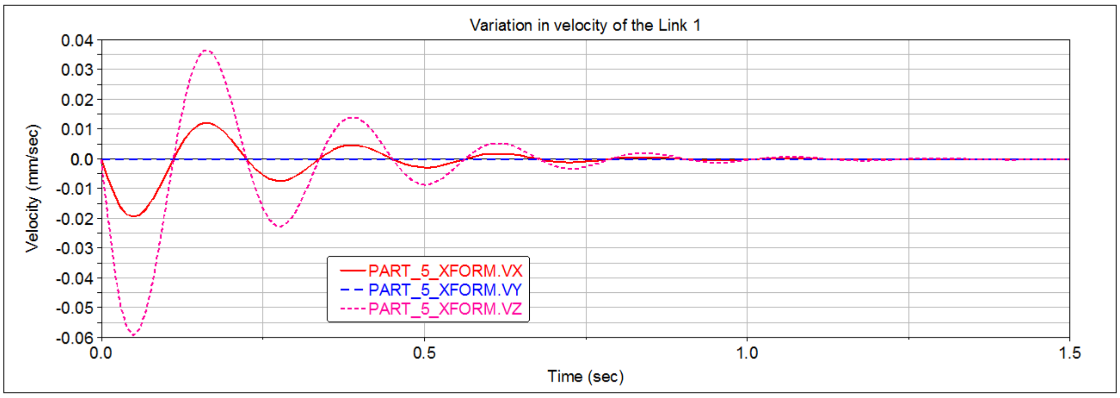


Fig. 4.26. Change in velocity of CM1 with steel

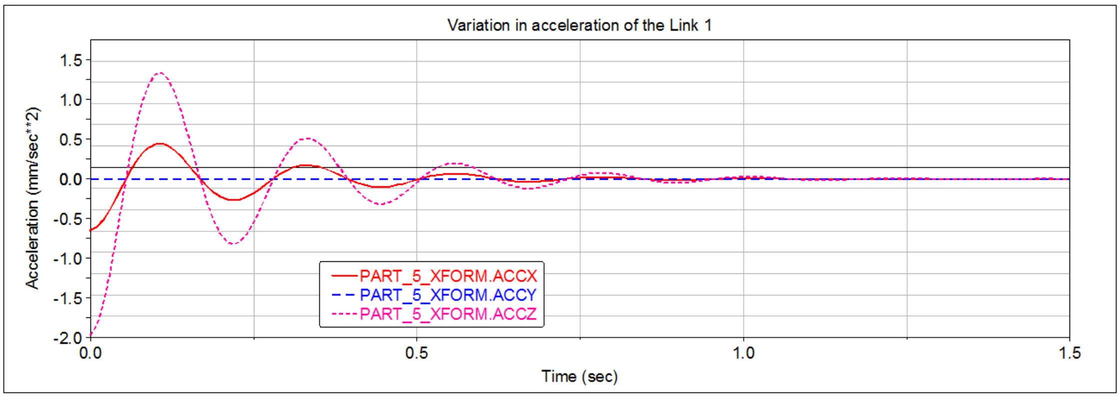


Fig. 4.27. Change in acceleration of CM1 with steel

- Link 2 CM

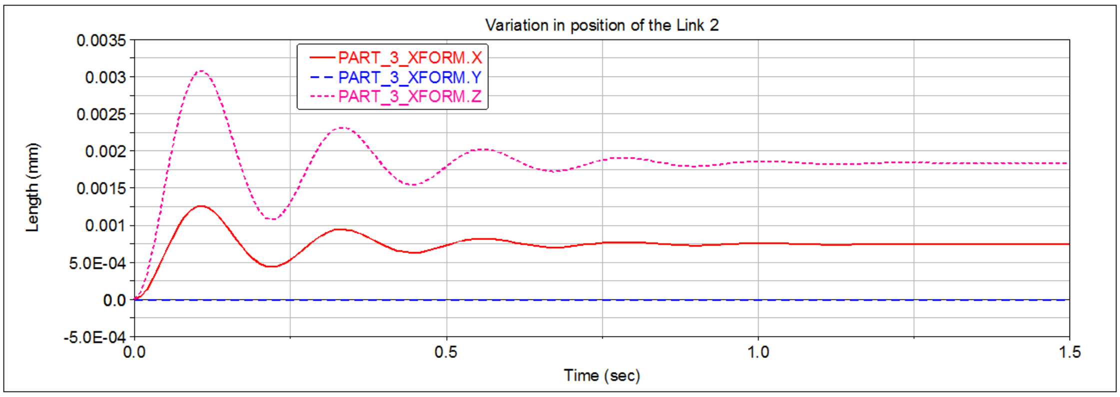


Fig. 4.28. Change in position of CM2 with steel

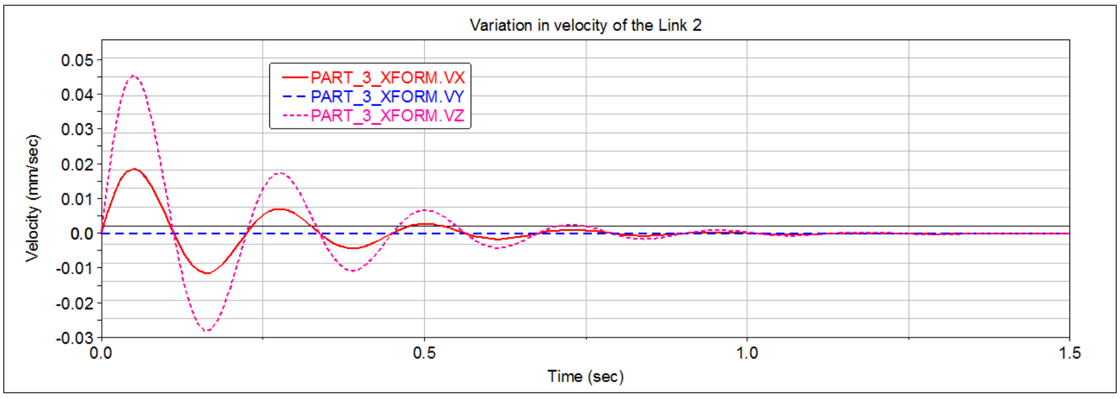


Fig. 4.29. Change in velocity of CM2 with steel

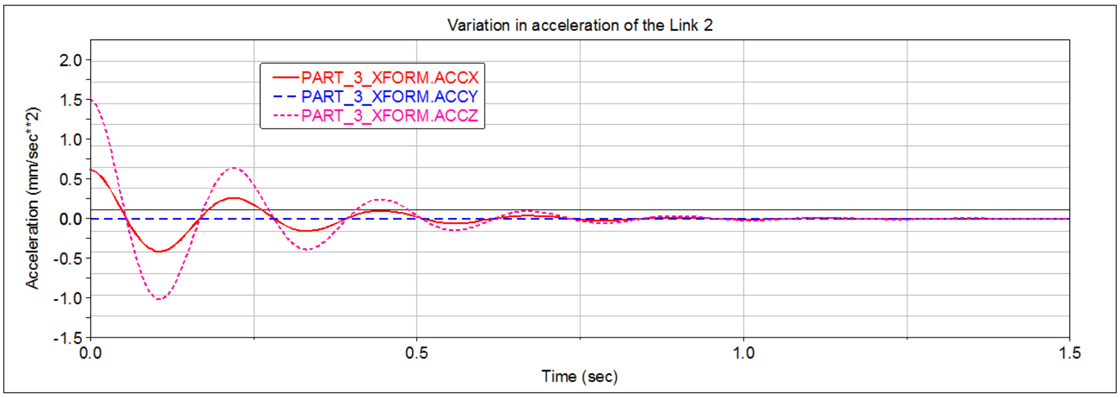


Fig. 4.30. Change in acceleration of CM2 with steel

• Link 3 CM

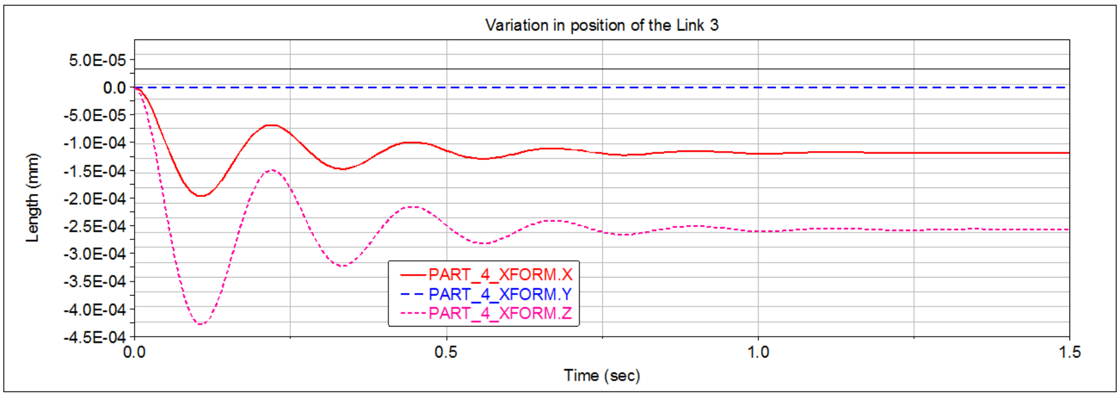


Fig. 4.31. Change in position of CM3 with steel

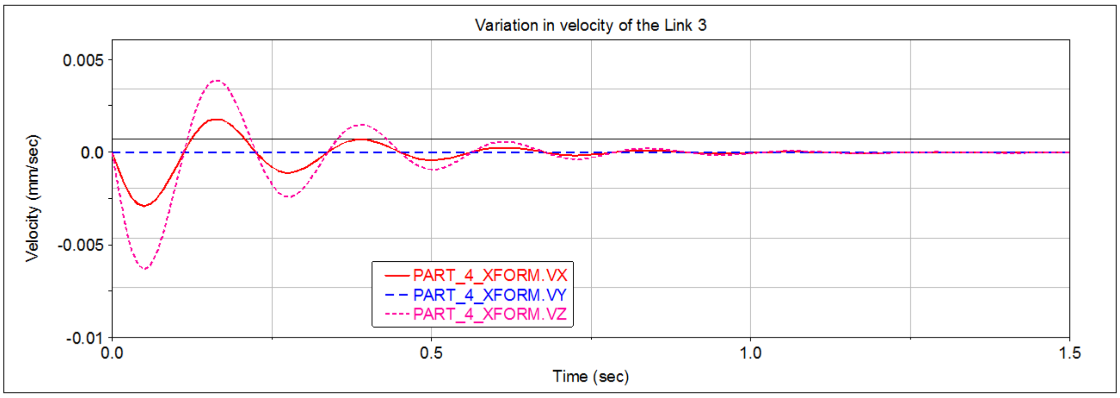


Fig. 4.32. Change in velocity of CM3 with steel

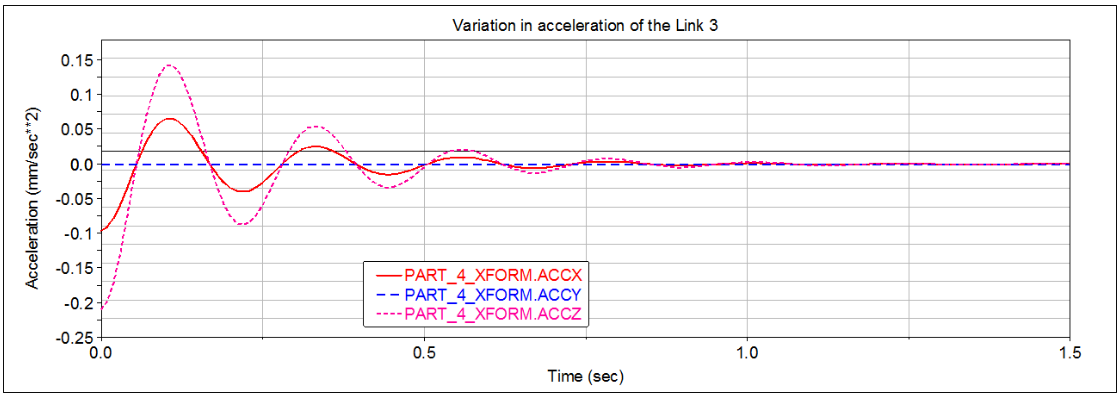


Fig. 4.33. Change in acceleration of CM3 with steel

From the graphs obtained in ADAMS/PostProcessor the displacements, velocities and accelerations are so small so the system can be considered to be in static equilibrium. So the analytical study calculated in the previous part was correctly done and the results have been checked in the program.

The next step would be to find the minimum force that should need to be applied in the Link 3 in order to break the static equilibrium of the model and be able to retract the landing gear. In the real model the force is done as:

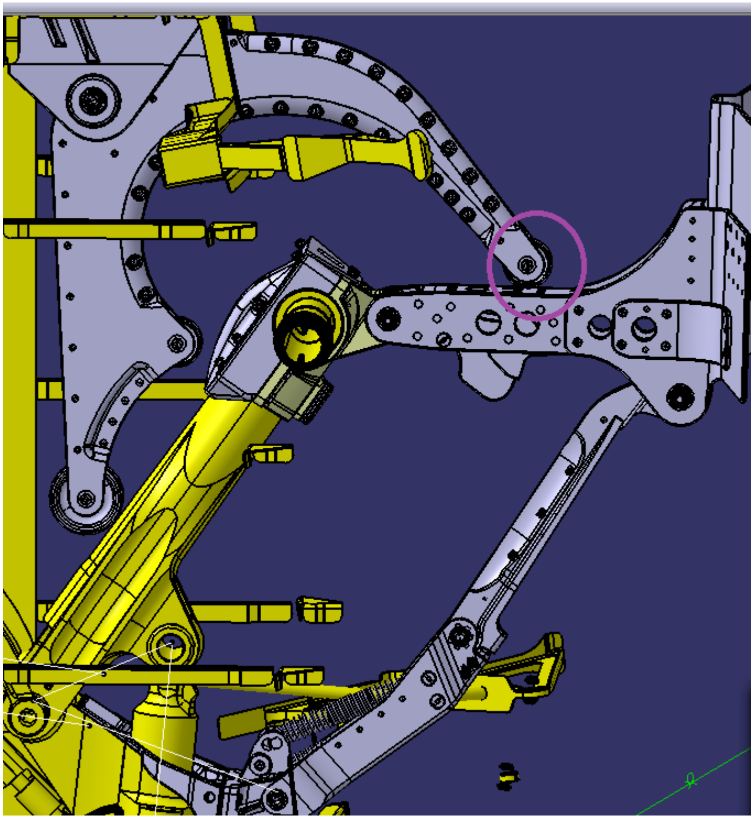


Fig. 4.34. Real application of the force in CATIA V5

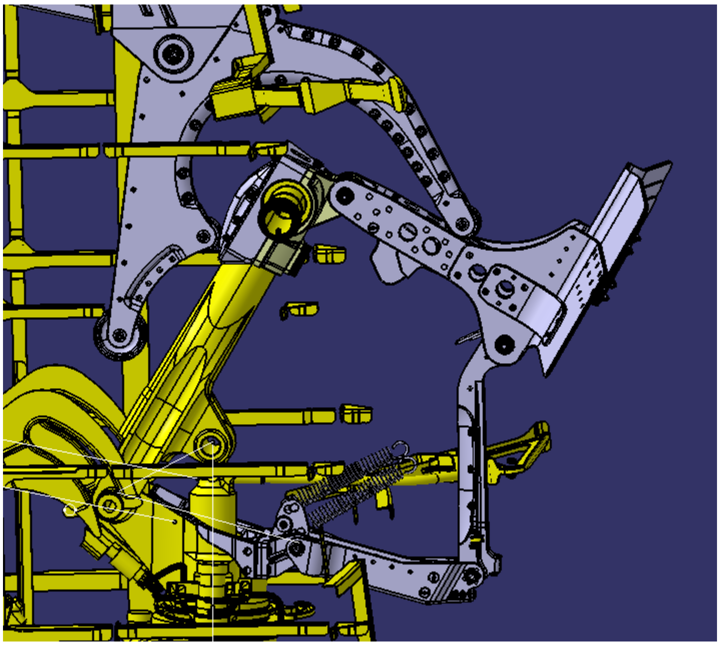


Fig. 4.35. Retracting mechanism in CATIA V5

The main goal of this study is to find the minimum force that needs to be applied and the optimum position for the application. For that, several forces has been applied in the program varying the application point from Point D until the real point of application of the model, because from so no, there is a curved shape so it would not be optimum to apply the force there, a sketch is in Figure 4.36.

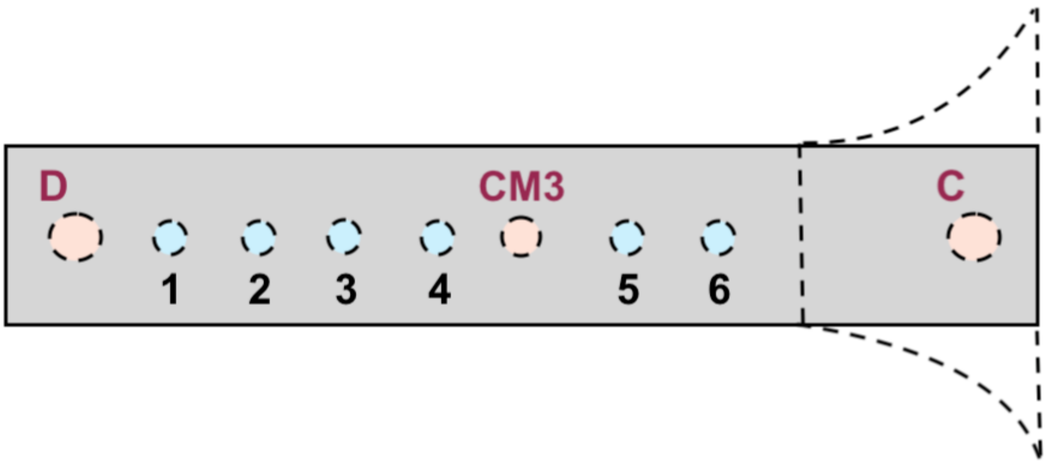


Fig. 4.36. Points of application of the force

From the study that has been done, it can be clearly said that when the force is applied more to the right of the link, the required force to retract the gravel deflector is lower and the time for that to happen is also smaller. So a table has been created to see how the force values varies depending on the position and a summarize of the declared point is also shown.

Position	**Magnitude (N)**	**Time (s)**
1	1070,115	1,92
2	535,147	1,82
3	356,713	1,68
4	267,533	1,66
CM3	216,312	1,32
5	197,995	1,5
6	182,543	1,42

Table 4.2. MINIMUM FORCE DEPENDING ON THE POSITION OF APPLICATION (STEEL CASE)

In order to make a more deep study of this piece, several modifications are going to be done to see how they affect the model. The first one is to introduce flexible parts in the model, which are going to be Link 1 and Link 2.

In order to work with a Flexible part, different ways are available in the program. The mesh can be created in a specialized program in finite element analysis and be exported into ADAMS in a file .MNF . But here the tool "Rigid to Flex" is going to be used in a first approximation and ADAMS will create the mesh for the links. When using this, ADAMS/ViewFlex is open and the settings are shown in the following image:

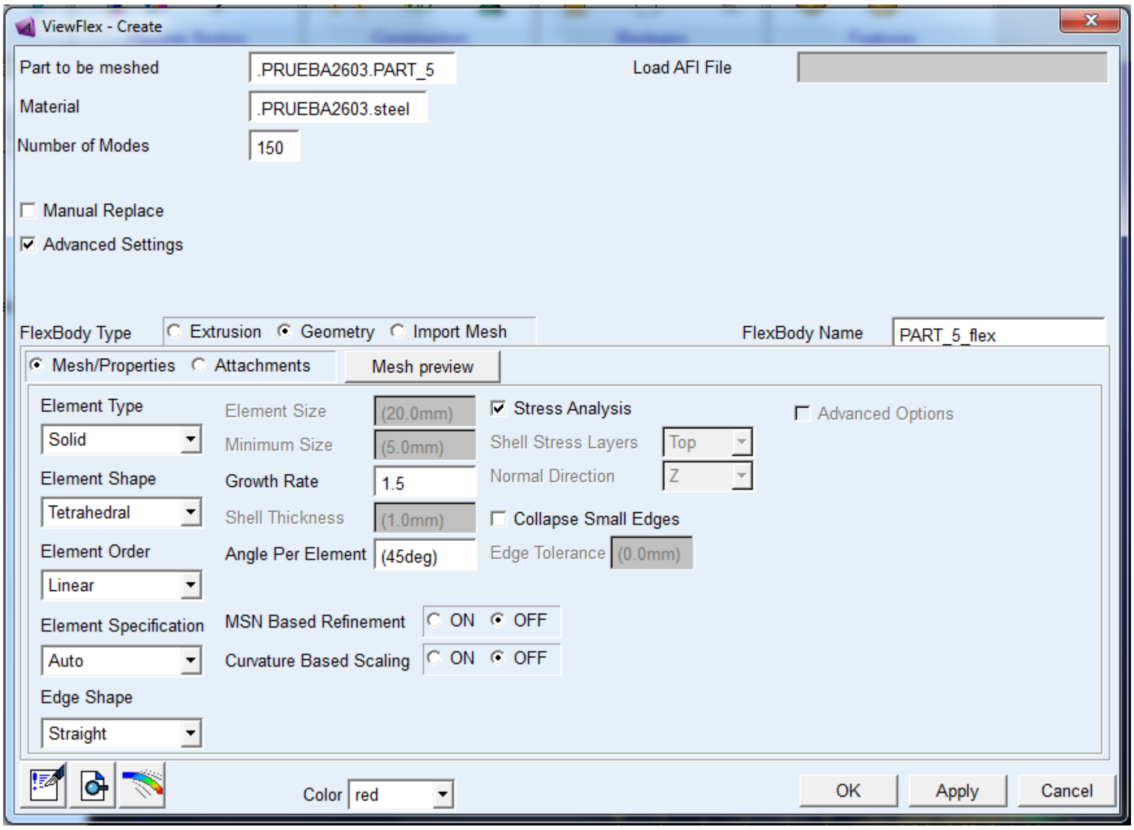


Fig. 4.37. Advanced Settings for creating a Flexible body

So with these advanced settings different characteristics can be changed so the mesh would depend on those choices. After the mesh is created, the 'message window' would appear and the information about the number of nodes and the number of elements of the mesh are displayed in it. For the case using the previous data, the mesh of the Link 1 and Link 2 look in ADAMS as:

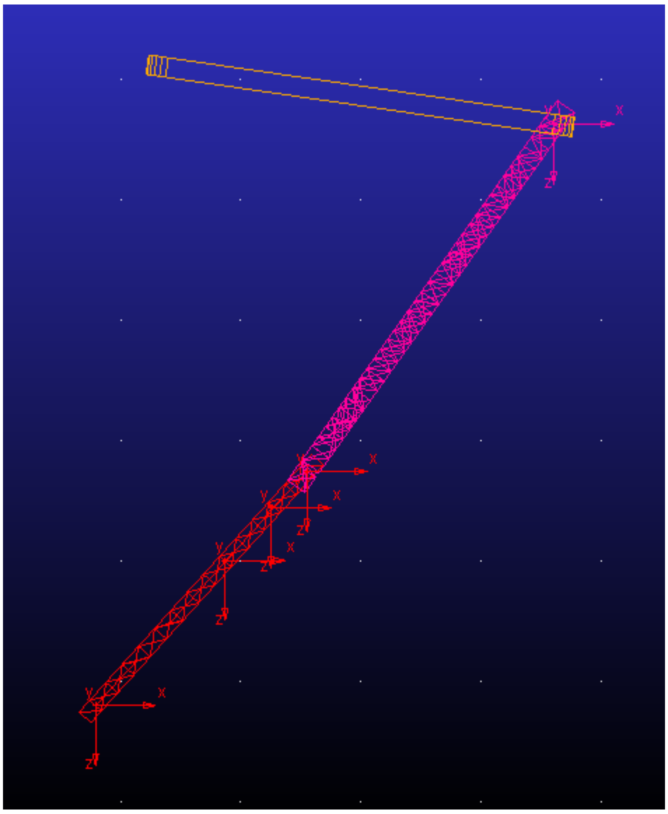


Fig. 4.38. Created mesh for Link 1 and Link 2 in ADAMS

Once the flexible bodies are defined, the stresses suffered by those pieces can be seen during the Simulation.

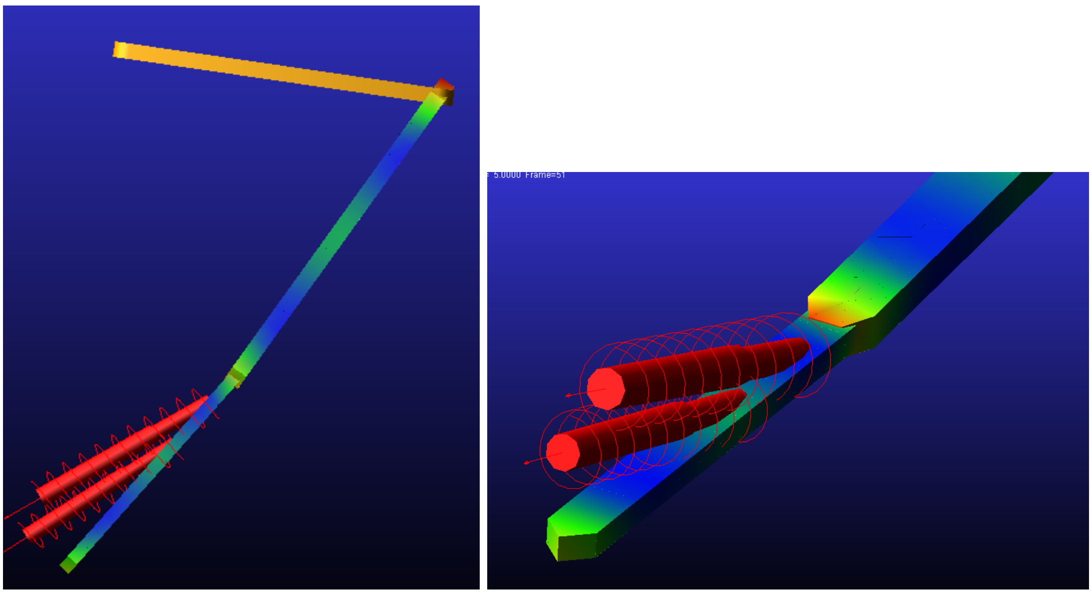


Fig. 4.39. Stresses in static equilibrium model

The previous photos show the stresses that the links suffer when the system is in static equilibrium. But the more important stresses to check are the ones that occur when the optimum load is applied and they are:

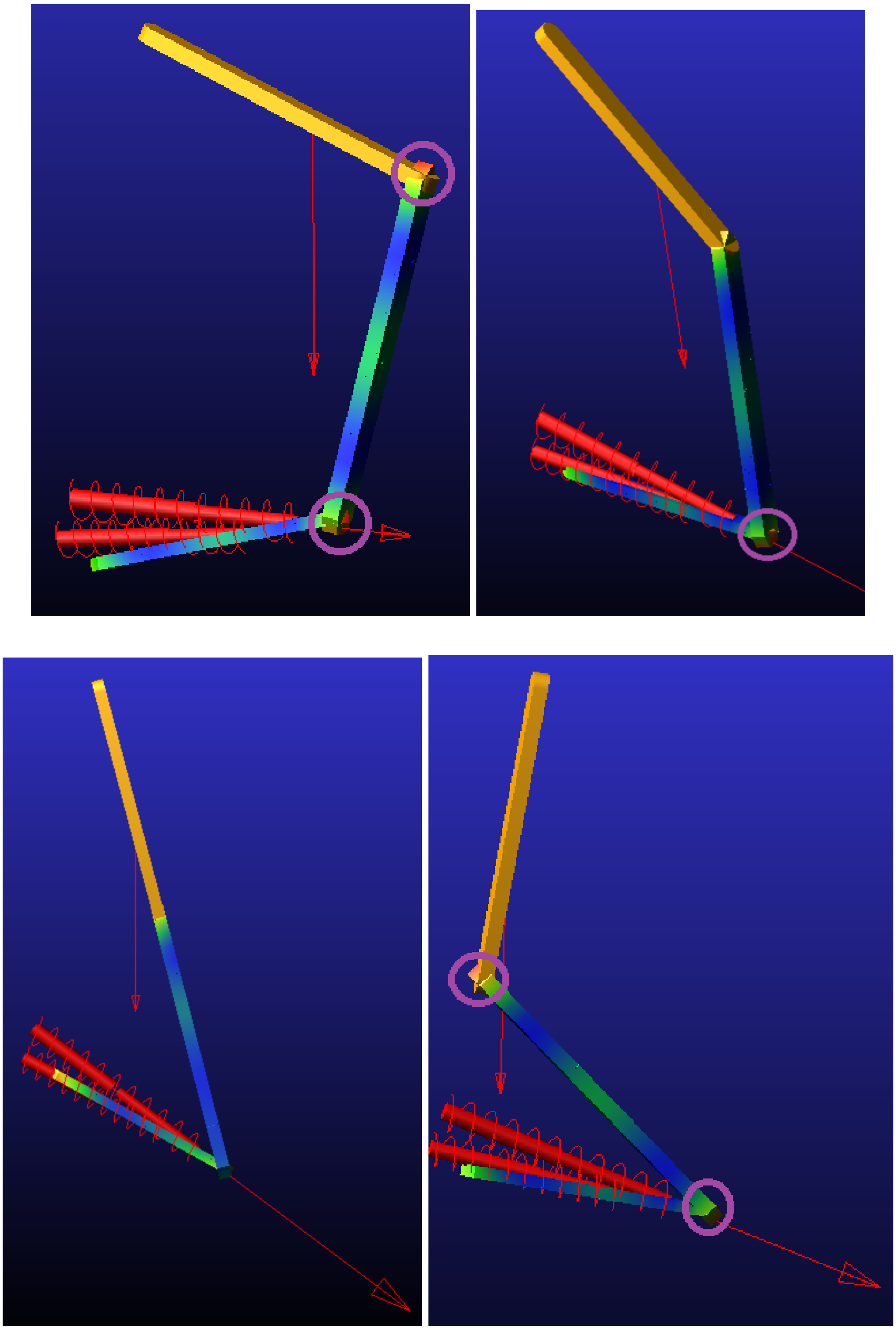


Fig. 4.40. Stresses in static equilibrium model

After that, some modifications are going to be done in order to analyzed their influence in the system. The first one is going to be the change of materials for the links. The previous model was done by steel because it is the default one when working with ADAMS. Data of some materials that ADAMS got in its database can be found in Table 4.3:

Material	**Young's Modulus** (N/m^2)	**Poisson's ratio**	**Density** (kg/m^3)
Aluminium	7.1705 E+10	0.33	2740.0
Cast iron	1.0 E+11	0.211	7080.0
Steel	2.07 E+11	0.29	7801.0
Stainless Steel	1.9 E+11	0.305	7750.0
Magnesium	4.48 E+10	0.35	1795.0
Nickel	2.07 E+11	0.291	7750.0
Glass	4.62 E+10	0.245	2595.0
Brass	1.06 E+11	0.324	8545.0
Cooper	1.19 E+11	0.326	8906.0
Lead	3.65 E+10	0.425	11370
Titanium	1.02004 E+11	0.3	4850.0
Tungsten	3.447 E+11	0.28	19222
Wood	1.1 E+10	0.33	438.0

Table 4.3. INFORMATION OF DIFFERENT MATERIALS

Now, different materials are going to be tested, so new preloads are going to be needed because the weight of the structure is going to change and the stresses are going to be different too.

ADAMS got several materials in its database that can be used for the created parts as it was shown before, but new ones can also be added. In order to do so, the first thing is to open the "Command Navigator" after clicking on "Tools" and once the Figure 4.41 appears, deploying the menu for Material just click on create and the following screen from Figure 4.42 would appear. In this last part, it can be easily seen that the only data needed for defining a new material are density, Young's Modulus and Poisson ratio.

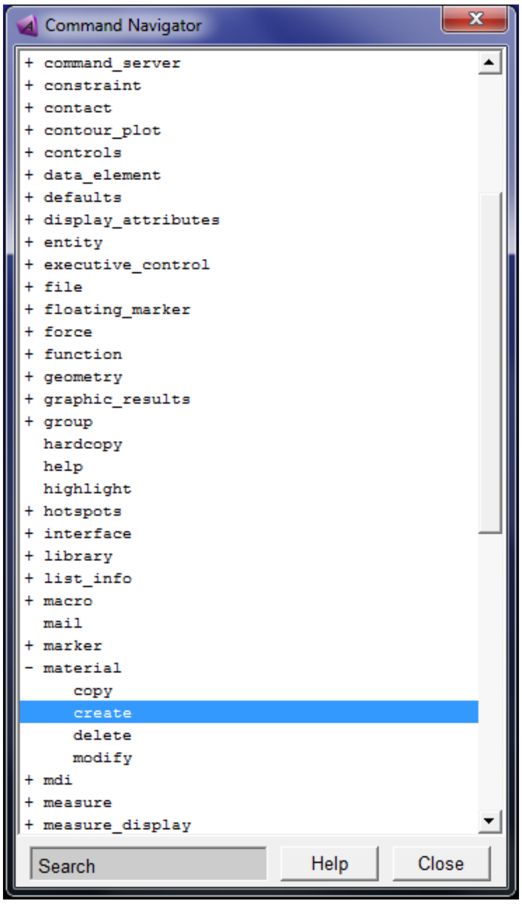


Fig. 4.41. Command Navigator in ADAMS View 2017.2

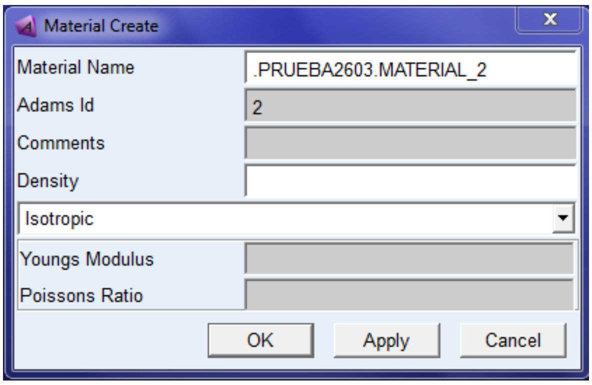


Fig. 4.42. Material Creation settings

In landing gears some parts also included titanium and different titanium alloys, which properties can be found in [20].

With these modification the new weights of the structure are:

W1	W2	W3
4.621 N	11.383 N	8.798 N

Table 4.4. WEIGHTS OF THE LINKS MADE OF TITANIUM

So the preload obtained with these weights are smaller than the ones for the steel. Here the procedure followed has been the same than for Steel. So when introducing the preloads in the springs it can be easily seen in ADAMS/PostProcessor how the system is in equilibrium:

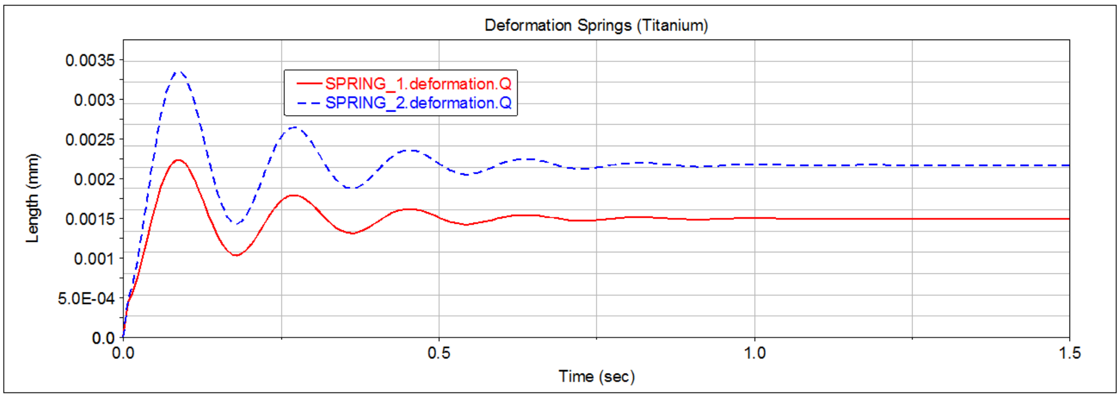


Fig. 4.43. Deformation of the spring in equilibrium with titanium

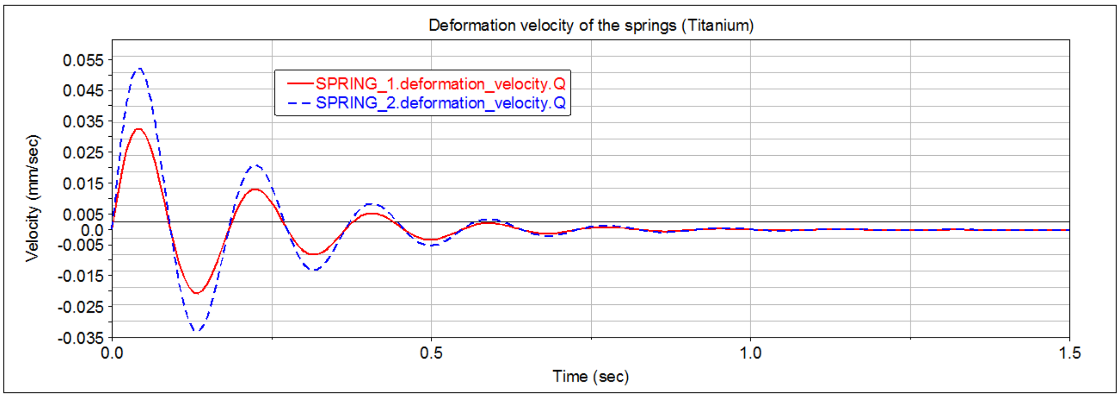


Fig. 4.44. Deformation velocities of the spring in equilibrium with titanium

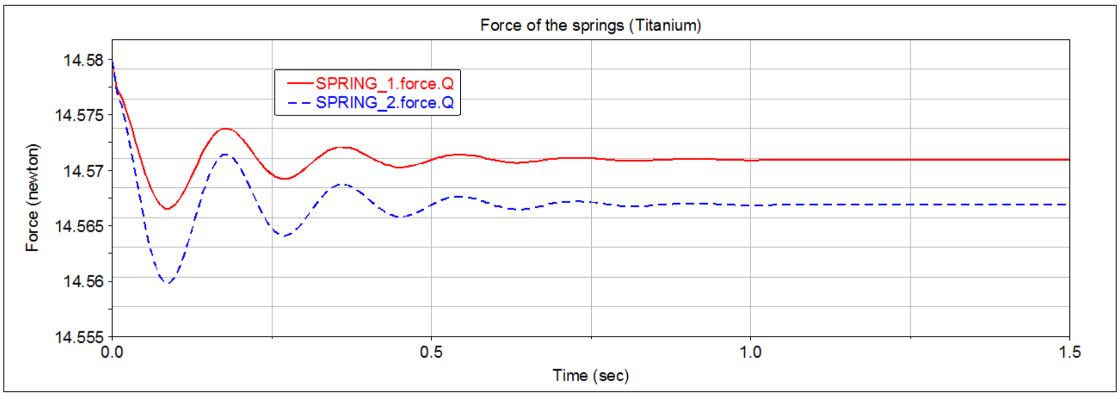


Fig. 4.45. Forces of the springs in equilibrium with titanium

The displacements, velocities and accelerations of the CM of the links can be also visualize in ADAMS/PostProcessor:

- Link 1 CM

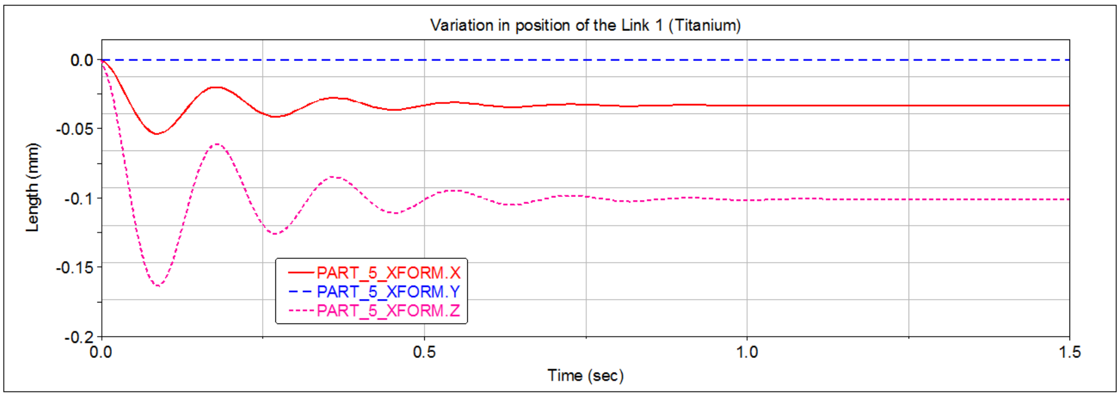


Fig. 4.46. Change in position of CM1 with titanium

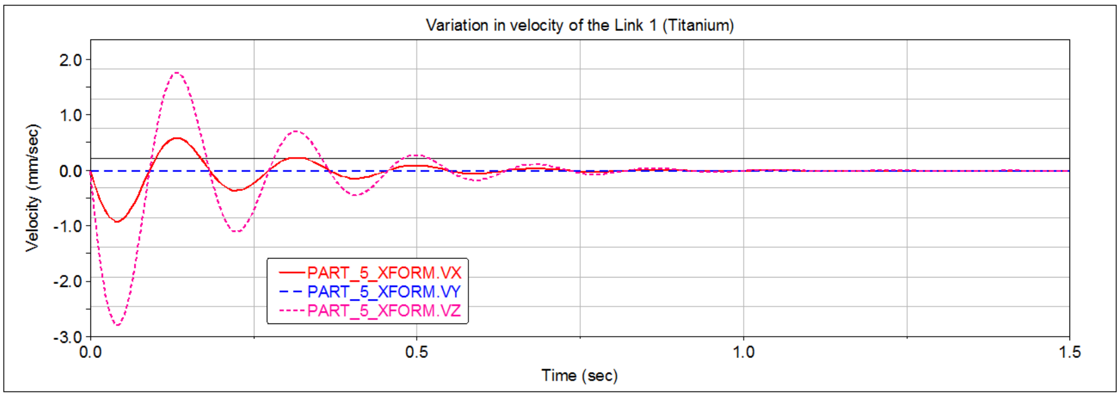


Fig. 4.47. Change in velocity of CM1 with titanium

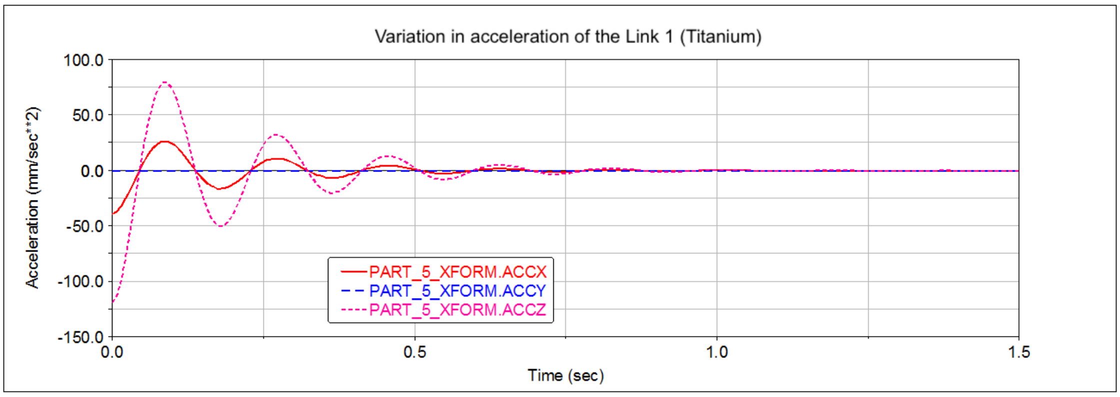


Fig. 4.48. Change in acceleration of CM1 with titanium

- Link 2 CM

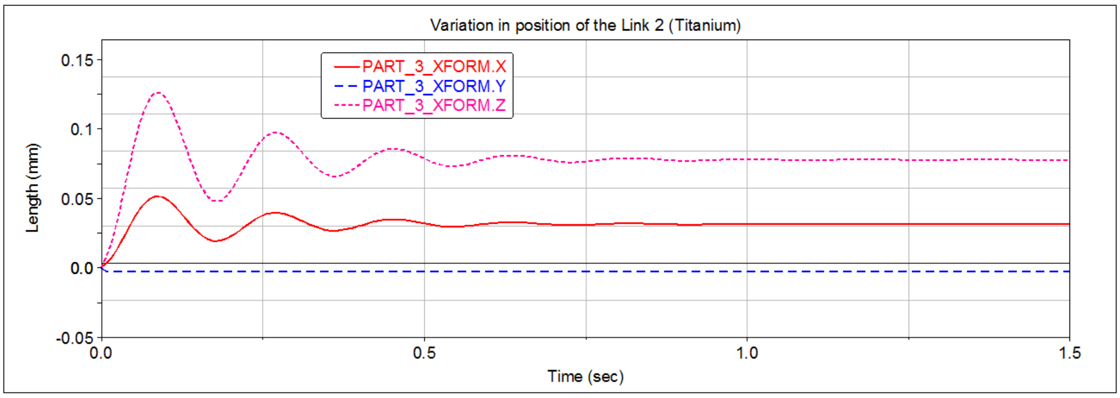


Fig. 4.49. Change in position of CM2 with titanium

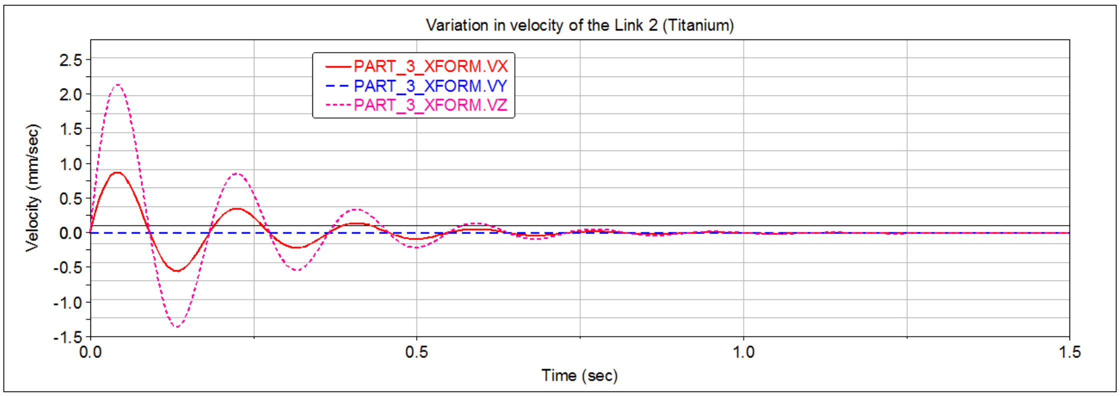


Fig. 4.50. Change in velocity of CM2 with titanium

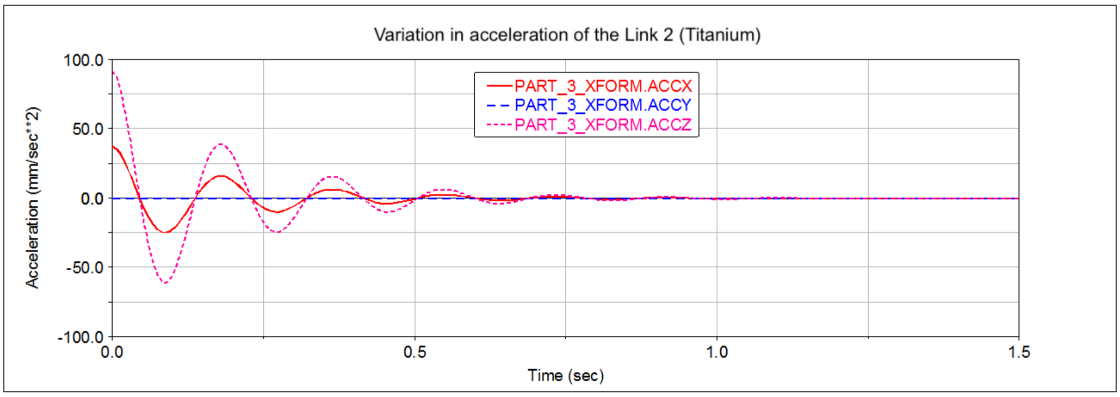


Fig. 4.51. Change in acceleration of CM2 with titanium

- Link 3 CM

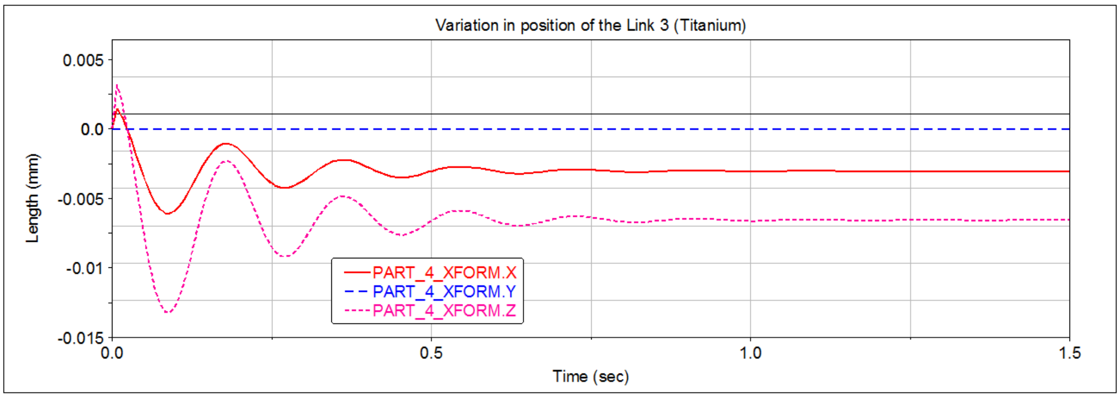


Fig. 4.52. Change in position of CM3 with titanium

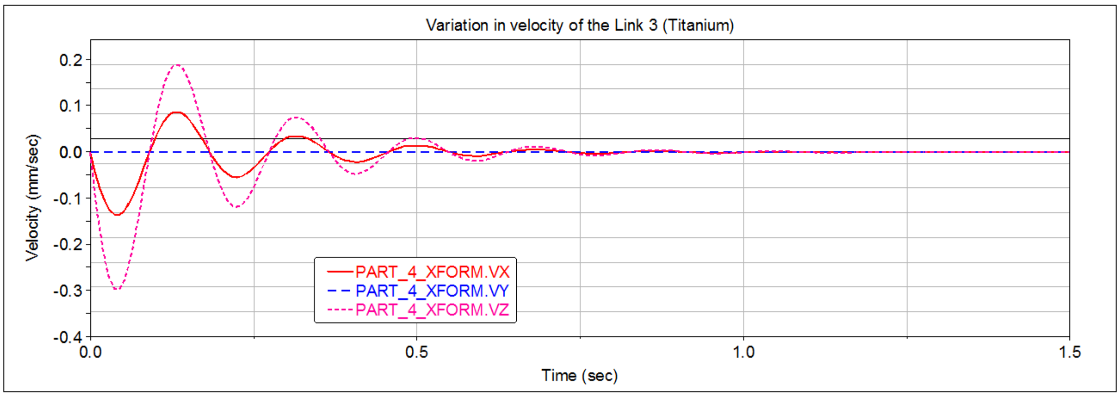


Fig. 4.53. Change in velocity of CM3 with titanium

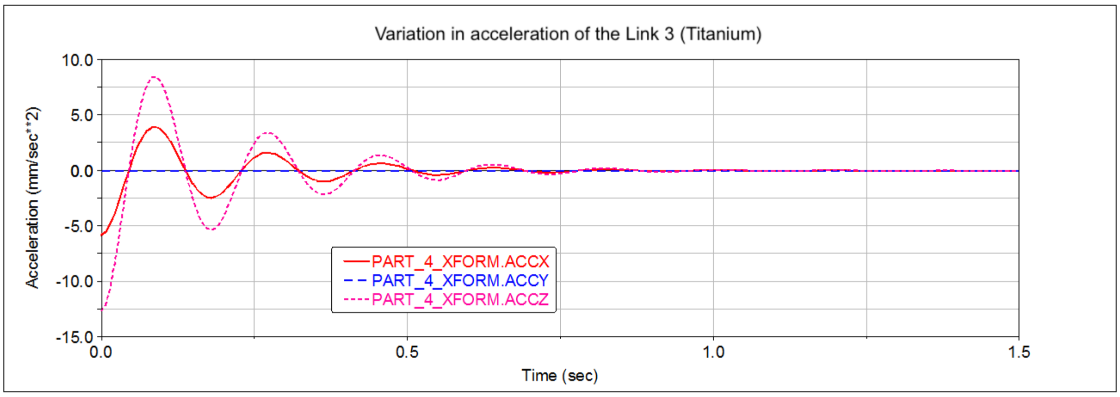


Fig. 4.54. Change in acceleration of CM3 with titanium

With the previous information that can be extracted from the graphs, the system is in equilibrium with a small deformation at the beginning but it soon stabilize around 0.8 seconds. That first deformation could be mitigated introducing friction in the connections between the Links. And now the new forces required to break the systems in these conditions are:

Position	Magnitude (N)	Time (s)
1	988,98	1,23
2	494,58	1,155
3	329,67	1,17
4	247,25	1,2
CM3	199,9	1,365
5	183,56	1,368
6	169,25	1,032

Table 4.5. MINIMUM FORCE DEPENDING ON THE POSITION OF APPLICATION (TITANIUM CASE)

Finally, the same study has been done with Aluminum as the material for the pieces, because is the material of the Gravel Deflector. In which the default masses were smaller, as it was expected, so the preload for the equilibrium and the minimum forces to break the equilibrium were even smaller than the previous ones of Steel and Titanium.

Until here, the goal of the previous studies have been a first contact with the piece of study and learn how to change different characteristics in ADAMS in order to see how they can affect the results. But now the characteristics of the real piece have to be introduce into the model in order to compare them with the virtual model that has been created by other department and later, compare also these results with the physical test realized.

The tricky part of this mechanism is the contact force between Link 1 and Link 2. Without this force the preload of the springs would be much less, which was the previous cases, but in the real model the preload of each spring is 21.2 times the weight of the structure, which is huge. So that preload is required in order to compensate that contact force, that is necessary to establish the relative position of Link 1 and Link 2.

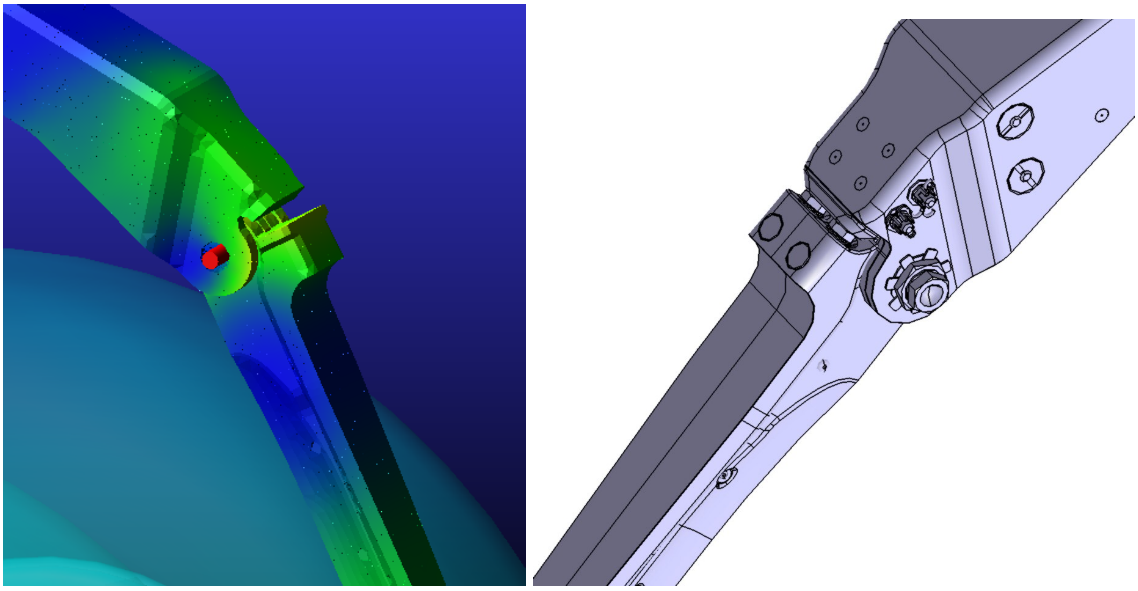


Fig. 4.55. Location of the contact force

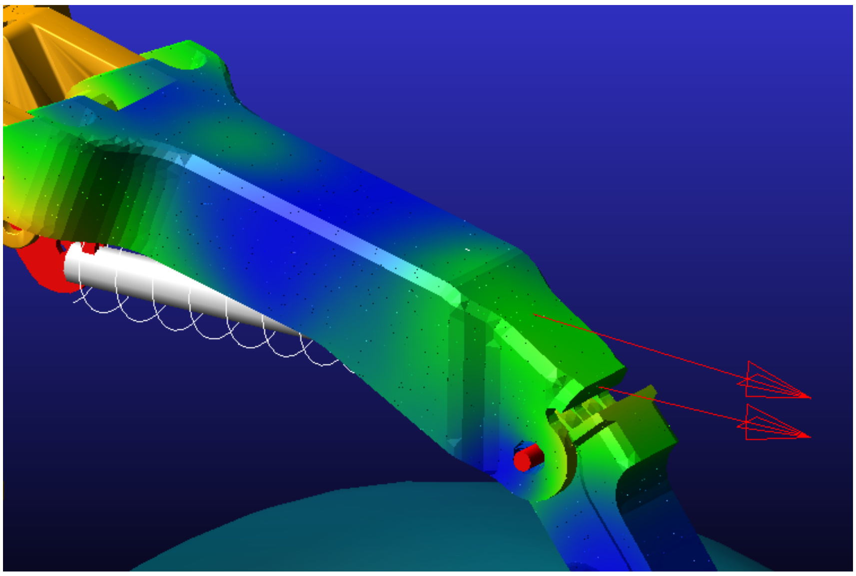


Fig. 4.56. Real Upper Link shape

So the contact force has to be introduce in our model. In order to simplified it, because the real shape of the piece is not going to be recreated, is going just to be defined the moment created by the force multiplied by the distance from the point of application until point B, is can be seen in Figure 4.57.

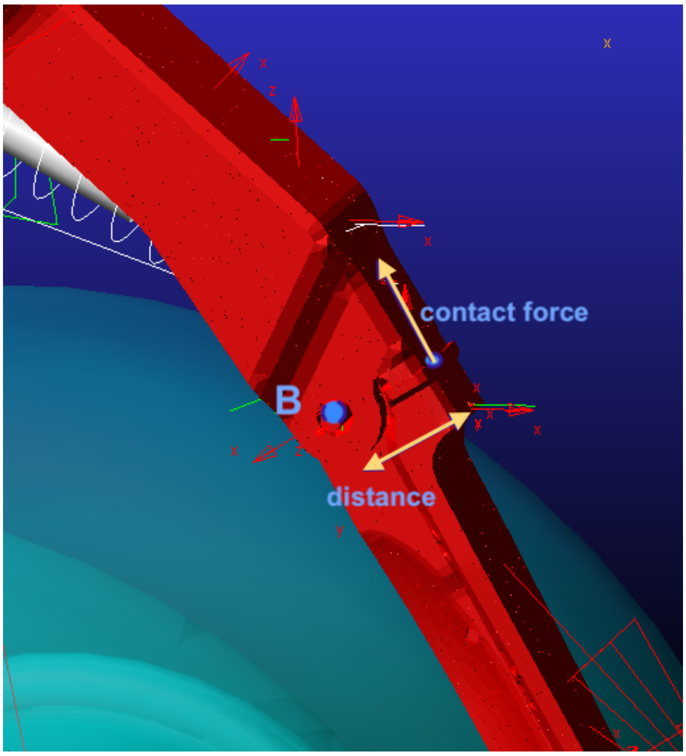


Fig. 4.57. Real Upper Link shape

After that, another important parameter has to be introduce in the model, there is a torsional spring acting between Link 2 and Link 3, with a specified preload, shown in Figure 4.59. So that has to be defined in ADAMS too. Finally the last modification that is going to be done in comparison with the previous simplified analysis is going to be the position of the linear springs, which are almost parallel. The good location can be seen in Figure 4.58.

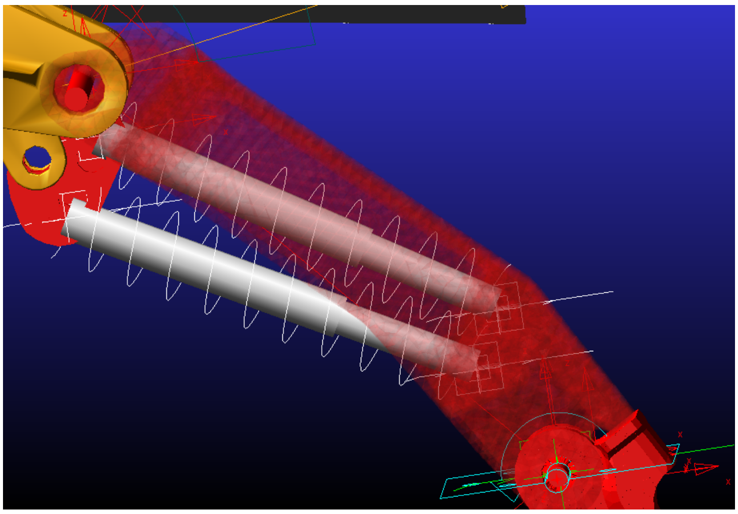


Fig. 4.58. Position of the springs in the complete ADAMS model

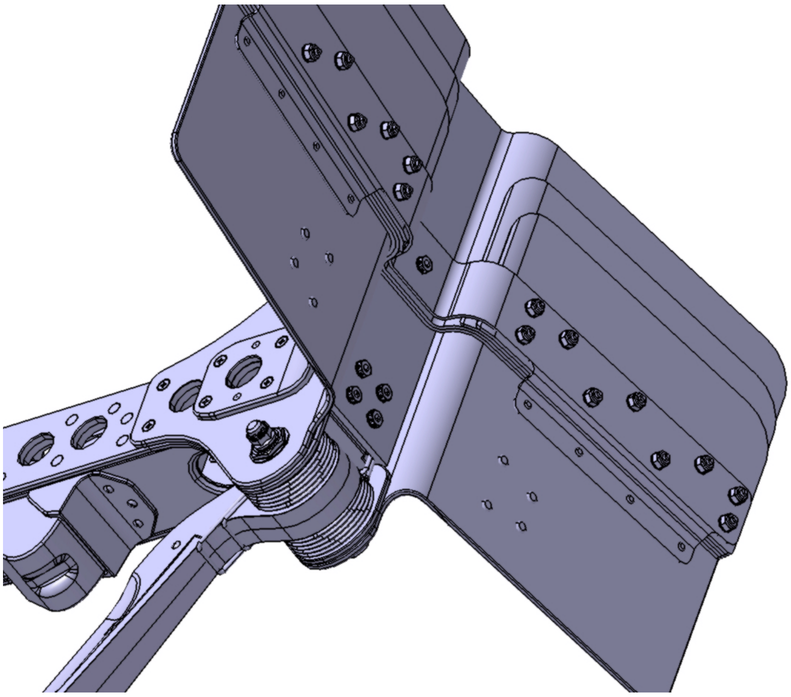


Fig. 4.59. Torsional Spring in the Gravel Deflector

With all the previous modifications, the model looks like:

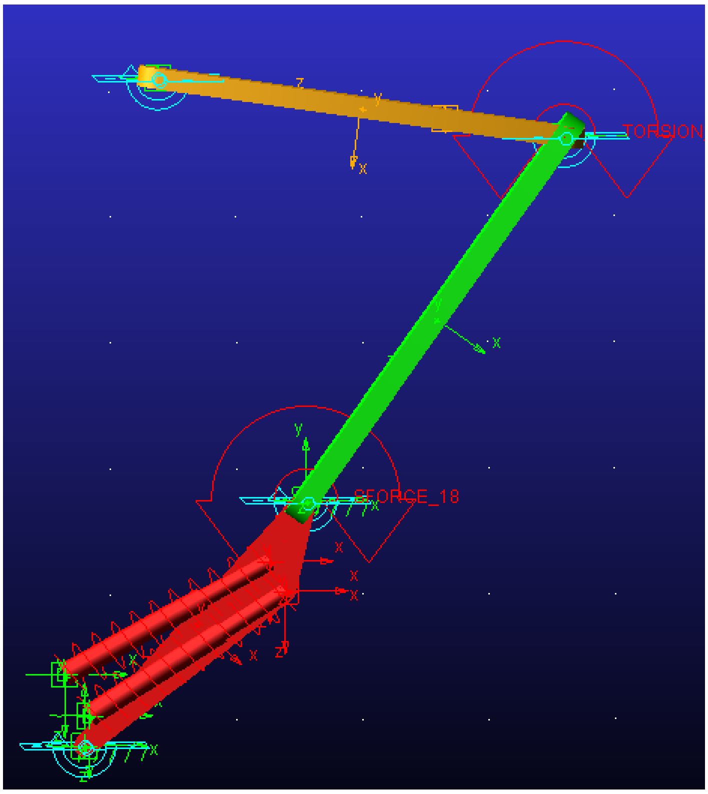


Fig. 4.60. Final simplified model in ADAMS

Finally with all the modifications that have been done, the next step would be to compare this simplified simulation with the one created by the Landing Gear Department. The approach followed has been:

- Mass of the Links are the same as the mass of the piece that they replace.
- Inertial characteristics of the pieces are going to be introduce in the Links.
- Information about the torsional spring is the same as in the complete model.
- Information of the linear springs do not change neither.

So the only unknown would be the value of the moment created by the contact force. In order to find it, an analytic study similar to the previous ones has been done taking into account the moment in C (torsional spring) and in B (contact force moment).

With that analytic procedure a value for the moment has been found and introducing it into the simplified model in ADAMS, it has been tested out that the mechanism is in equilibrium. The required value in ADAMS to get the equilibrium has been a 95.72 percent of the analytic result. And that was the first goal until here and it has been accomplished. Comparing that moment with the moment created by the contact force defined in the other model, the one created by the Landing Gear Department, multiplied by the distance, it can be said that my simplification is quite accurate since the value obtained in ADAMS has been a 90.54 percent of the real value.

Here is important to remark that in order to eliminate the first deformation of the system that has been noticed in all the graphs of ADAMS/PostProcessor, the real friction has been introduced in the joints between the bars. Then, the next thing that needs to be calculated with the simulation is the minimum force to break the equilibrium, as in the previous part. For that, the force is defined in the point 6 (Figure 4.36) as it is the optimum point of application.

Once the force is applied, doing an iteration, the minimum value required to break the equilibrium has been 5.4 kg higher than the one predicted with the complete model.

5. PHYSICAL TEST OF THE PIECE OF STUDY

As it has been discussed at the beginning of the thesis in order to validate the results obtained in a virtual simulation, the physical test is still needed in order to compare both results. So that has been the aim of this part in which the Gravel Deflector has been submitted to a physical test in which it would simulate the same that the virtual simulation intends to do.

The arrangement of the physical mechanism can be seen in the following images:

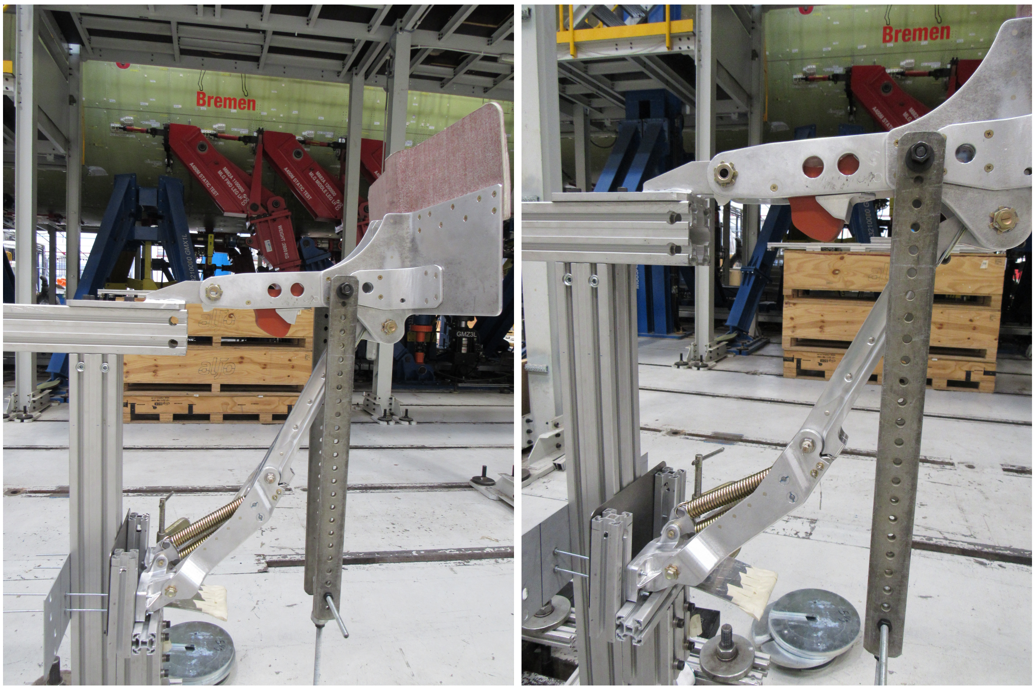


Fig. 5.1. Real gravel deflector at the day of the physical test

So in order to find the minimum load to break the mechanism, several weights are situated in the support until the piece broke. This is not the optimum way of doing it because the placement of the weights has been manually so the intensity of dropping the weights affect the results due to the inertia. But it has been due to the little time available to do it because the piece is being studied in another location of Airbus Spain.

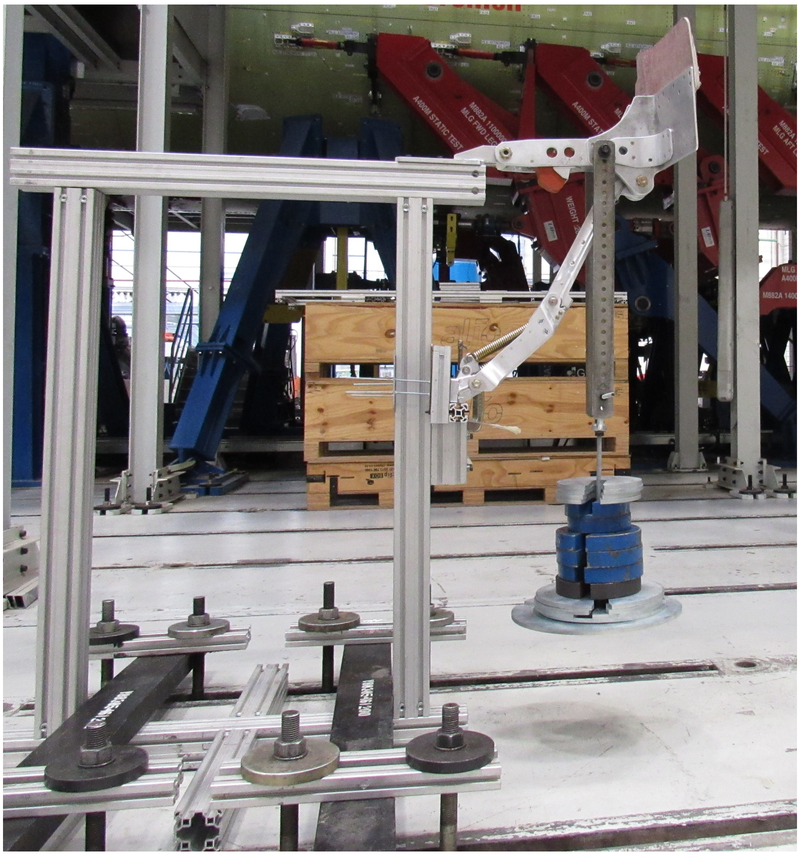


Fig. 5.2. Real gravel deflector with weights at the physical test

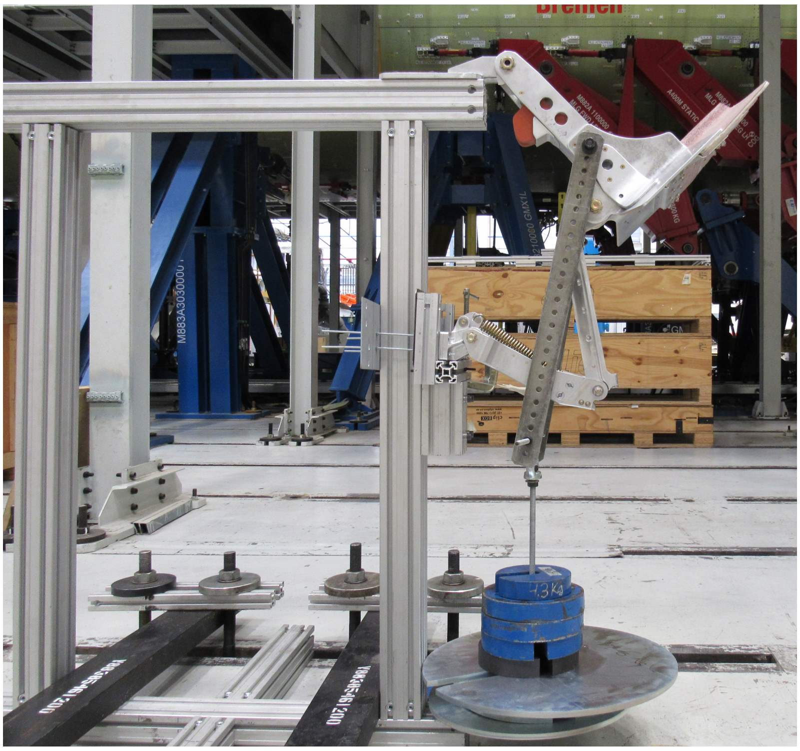


Fig. 5.3. Real gravel deflector after the break at the physical test

And in Figure 5.4, the structure created for the test can be visualized better:

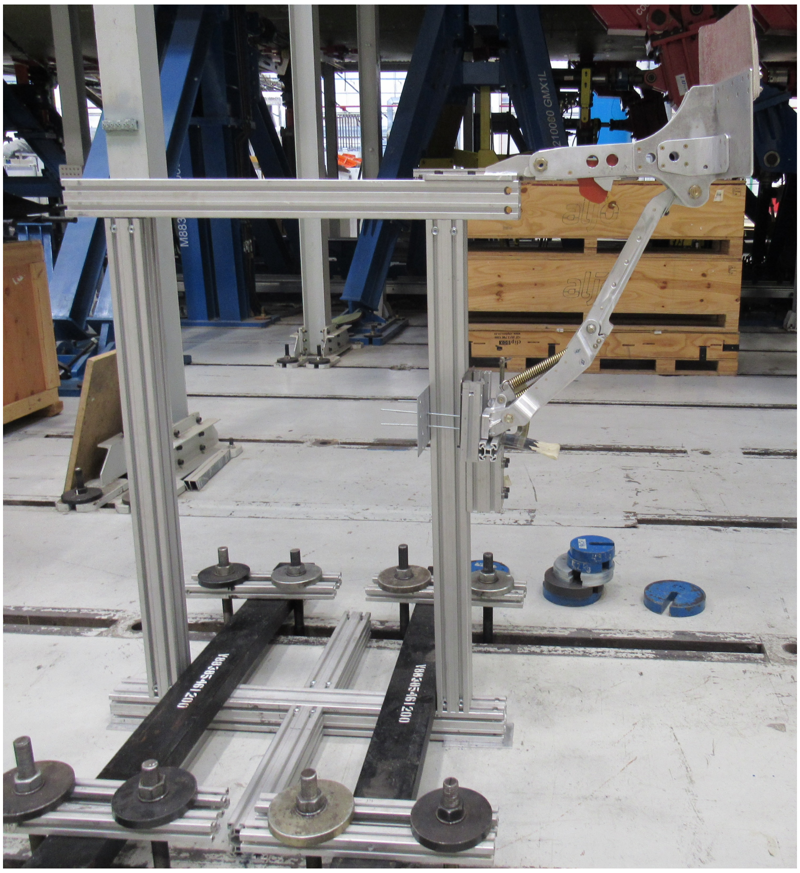


Fig. 5.4. Structure used at the physical test

The test was repeated several time in order to interpolate the results obtained in each of them to get the more accuracy as possible. So with that configuration the minimum force to break the equilibrium of the Gravel Deflector was around 75-85 kg.

The results obtained in the physical test have been much higher than the ones expected, 30 kg more than predicted. And obviously that is a problem in the performance of the retraction of the NLG.

For that, Airbus has been in contact with the Canadian Company in charge of the manufacture of the piece in order to find the error and fix it. Finally, it has been found that the friction in the joints was so high in the specimen and that is the reason why higher force was required the day of the test.

The friction can be regulated, according to the company, so a new test is going to be performed but with the same friction that was defined in ADAMS in order to compare again the results. Also once the specimen arrived to Getafe, the springs of the mechanism were not the same of the specifications, so the characteristics of the springs have to be changed in ADAMS in order to get the more accurate result as possible.

6. CONCLUSIONS

Several conclusions have been reached at the end of this thesis. The most important one is that even if unfortunately the results of the simulation realized does not correspond to the ones obtained during the physical test, I really believe that virtual test can be implemented in a company and take great advantages from its properties.

The wrong approach about this thesis have been the piece chosen for the study. This piece is manufactured by a Canadian company and then the complete model in ADAMS was created by the Landing Gear Department in Airbus DS in Getafe, different from the one that I am working in. So problems in the communication and transmission of data have been present since the first day.

After trial and error, because the information obtained was not always the updated one, the simplified model realized in this thesis has given very accurate results when compare them with the complete simulation in ADAMS of the Gravel Deflector. It has also helped the analytical analysis to know that the results of the simulation were correct.

Once the physical test was done, it was checked that the complete model in ADAMS created by Landing Gear Department did not predict the real mechanism neither. Because they predicted that the minimum force to break the mechanism was almost half of the real one.

This is a perfect example of how even if they have been working in that model for 2 years, there are still modifications that have to be implemented in order to obtain the correct results.

And it gives the opportunity of realized how important is the communication and sharing when working with different companies. Because in this case, the main problem has been that the Canadian company did not give all the information updated and when the physical test was performed, the springs installed were different and the friction could be regulated, and that is the reason why a new test is going to be carried out.

As it has been seen with the technical papers studied, some companies have dedicated several years to the development of this tool and they are obtaining real results that help in their daily work.

In order to develop the skills necessary a company needs to have in mind that is a very long process until getting real beenfits and a lot of money should be invested in it. Obviously, it is needed a full team completely devoted to virtual testing.

The first phase would be time for research, similar to the one that this thesis inteds to do, in order to find the best software for the company objectives. After that a team should learn the program with the help of some experts on it who teach them. The next step would be to start developing small and simple simulations that can be compared with the results of physical tests.

This last phase is the most critical one becuase is the key to decide if the virtual results are useful or not. For that reason easy simulations and test are performed, as it was seen in the Pyramid of Tests, Figure 1.1. And then, when small components are controlled, more complex one will be done.

So to sum up, this prodedure takes a huge investment of time, people and money as it was said in [6]. But it was proved how many companies have applied it and the results are very satisfied. So finally, the use of virtual testing is beneficial in a company and advantages can be obtained.

BIBLIOGRAPHY

[1] T. Ulmer, J. Amin, and P. Neuhaus, "High lift system virtual test", *NAFEMS World Congress 2013*,

[2] M. Bruyneel *et al.*, "Damage modeling of laminated composites: Validation of the intra-laminar law of samcef at the coupon level for ud plies", *ECCM16 - 16TH EUROPEAN CONFERENCE ON COMPOSITE MATERIALS*, 2014.

[3] L. Critchley, *Computer simulations in engineering*. [Online]. Available: `https://www.statisticsviews.com/details/feature/10482673/Computer-Simulations-in-Engineering.html`.

[4] P.R.Spalart and V.Venkatakrishnan, "On the role and challenges of cfd in the aerospace industry", *The Aeronautical Journal*, vol. 120, no. 1223, pp. 209–232, 2016. DOI: `10.1017/aer.2015.10`.

[5] C. Inc, *Simulation software*. [Online]. Available: `https://www.capterra.com/simulation-software/`.

[6] J. Lescheticky, H. Hooputra, and D. Ruckdeschel, "Predictive crashworthiness simulation in a virtual design process without hardware testing", *SIMULIA Customer Conference*, 2010.

[7] H.Hooputra, H.Gese, H.Dell, and H.Werner, "A comprehensive failure model for crash- worthiness simulation of aluminium extrusions", *Int. J. of Crashworthiness*, vol. 9, no. 5, pp. 449–463, 2004.

[8] S. International, *Automotive design magazine*. [Online]. Available: `https://www.sae.org/publications/magazines/`.

[9] ——, "Goal: 'virtual' perfection", *Automotive Design Magazine*, no. September, pp. 24–25, 2015.

[10] AUTODESK, *¿qué es cad/cam?* [Online]. Available: `https://www.autodesk.mx/solutions/cad-cam`.

[11] D. Kato, Y. Nakahira, N. Atsumi, and M. Iwamoto, "Development of human-body model thums version 6 containing muscle controllers and application to injury analysis in frontal collision after brake deceleration", *IRCOBI conference 2018*,

[12] T. M. Corporation, *Toyota updates its thums virtual crash dummy software*. [Online]. Available: `https://global.toyota/en/newsroom/corporate/26497281.html`.

[13] G. Bernardini, "Hydro-mechanical modelling of the airbus a380 nose landing gear extension/retraction systems", 2009.

[14] A. Engineering, *Web site of the program*. [Online]. Available: `https://altairhyperworks.com`.

[15] I. de Diseño Electrotécnico S.L., *¿qué es altair hyperworks?* [Online]. Available: `http://www.indielec.com/que-es-altair-hyperworks-cms-4-50-374/`.

[16] M. Zhou *et al.*, "Applications of advanced composite simulation and design optimization", *Altair Engineering Resource Library*,

[17] A. Kueh and S. Pellegrino, "Abd matrix of single-ply triaxial weave fabric composites",

[18] A. Industry, "Altair's products and partners offering assist commercial vehicles seat manufacturer to enhance its development process", *Altair Engineering Resource Library*,

[19] M. Company, *Datasheet adams*. [Online]. Available: `http://www.caeinnovacion.es/autogestion/casos/pdf/160524123430.pdf`.

[20] C. Veiga, J. Davim, and A. Loureiro, "Properties and applications of titanium alloys: A brief review", 2012.

[21] P. Baguley, R. Roy, and J. Watson, "Understanding the cost of design evaluation using virtual crash testing",

[22] D. of Defense (United States of America), "Design criteria standard human engineering", vol. G, 2012.

[23] ——, "Standard practice system safety", vol. E, 2012.

[24] ——, “Test method standard for environmental engineering considerations and laboratory tests”, vol. F, 2000.

[25] ——, “Military standard electromagnetic interference characteristic requirements for equipment”, 1967.

[26] ——, “Military standardization handbook maintainability prediction”, 1966.

[27] ——, “Military handbook reliability prediction of electronic equipment”, vol. E, 1986.

[28] E. D. Agency, “Certification of military aircraft and related products, parts and appliances, and design and production organizations”, 2014.

APPENDIX I: COSTS

This Appendix has been created to discuss how the costs of the project would affect to the daily work of the company. For that reason, several research has been done in order to know how to face this part as [21].

The first step has been to divide the different costs in 4 different components that contribute to the overall budget. These components are:

- Labour
- IT infrastructure and Software
- Facilities
- Consumables

It is important to remark that the last two components (Facilities and Consumables) are not going to suffer any changes. Facilities component encloses Building of the offices taking into account the location and dimension and the office furniture, in which the factory of Airbus Getafe is of 840.00 square meters and the price of the square meter in its location is around 1.967 euros per square meter. And Consumables are spenses such as light, heating or power consumption of the computer.

So the interesting components are Labour which takes into account the human work realized and IT infrastructure and Software needed.

Estimation of Labour costs

The labour process realized to complete this project has been distributed in different parts, similar to the ones explained in the Chapter 2:

- Time of research

- Time to learn the program (manuals and solved exercises)
- Analytical study of the simplified model
- Creation of the model in ADAMS (including all the modification)
- Set up simulation and solving
- Interpretation of results
- Reporting

The following table summarized the money spent in each of the previous part, based on the time spend on it and the salary per hour:

LABOUR COSTS		
Research time	2 weeks	225 euros
Learn the program	3 weeks	337.5 euros
Analytical study	1 week	112.5 euros
Creation in ADAMS and simulation	6 weeks	675 euros
Interpretation results	2 weeks	225 euros
Reporting	2 weeks	225 euros

And in a similar way, the main costs for IT Infrastructure and Software are:

IT INFRASTRUCTURE AND SOFTWARE COSTS	
Computer	630 euros
Internet Access	No changes
License of MSC.ADAMS	Student Version Free

The price of the license of the program depend on the type of purchase chosen, the different types are:

- Purchase for unlimited time: Price 30.000 euros plus 9.000 euros pero year as maintenance.
- Purchase for one year: Price 6.000 euros per year plus 9.000 euros per year of maintenance so in total for one year, 15.000 euros.

During this development, purchase of one year has been used, increasing the total cost of the simulation process to around 17.430 euros.

Finally, in order to compute the benefits of applying virtual testing instead of doing the physical test, the money that would cost the test of the piece of study is going to be done.

It is important to realize that this piece is not manufactured by Airbus, so they have to purchase it to an external company. So the list of things necessary for the test would be:

- Man-hours pre-test: This refers to the time required for one person to be working in order to prepare everything for the test. It is important to notice that this test have been so simple so it just took round 100 hours to do it.
  Here the costs of the computer necessary have to be taken into account are the same calculated for "Computer in IT infraestructure and Software Costs" in the previous part.

- Man-hours post-test: Once the mechanical test is done, the work of the engineers does not finish there. Reporting is also an important phase in order to summarize the process and the results obtained.

- Adapted place to perform the mechanical test. This installation is not going to affect to the money of the project as Airbus has already good places where perform this kind of tests, so no more place needs to be adapted.

- Mechanics-hour: They have to fabricate and mounted the structure for the test.

- Required things during the test: In this part several things can be taken into account, that would be the costs of the pieces for the structure or the weights used. But in this case it has been a very low cost test because the materials from previous tests have been re-utilized.

- Finally the systems required have to be taken into account too. In this example just the recording system was used, but in some others it is needed the use of sensors, actuators...

So a rough estimation can be done in order to know the price of this test. For that case I am going to assume that the materials for the structure were purchase instead of re-utilizing the ones existing. So the total budget would be around 3.500/4.000 euros (without taking into account the price of the Gravel Deflector).

In this case doing the physical test has been cheaper but only because a "low cost" mechanical test has been done. But in the long term, the cost of the license for the virtual program would be amortized because it would not be used just for one project but instead, it gives you the opportunity to generate a wide range of simulations. And big mechanical test would need a lot of engineers and mechanics working on it.

APPENDIX II: REGULATORY FRAMEWORK

In aviation before uses any pieces in an aircraft they have to be submitted to different test in order to check its characteristics. And the gravel deflector studied in this thesis needs to accomplish several regulation before start using it. The main requirement that this gravel deflector needs to accomplish is the RS-145 that requests protection against damages caused by debris, water and slush.

But also apart from that requirement different military specifications and standards should be taken into account, some of them are summarize below in order to get a whole idea of the main specifications:

- MIL-STD-1472: ISSUE G [22]
  "This standard establishes general human engineering criteria for design and development of military systems, equipment, and facilities" [22].

- MIL-STD-882: ISSUE E [23]
  "This system safety standard practice identifies the Department of Defense (DoD) Systems Engineering (SE) approach to eliminating hazards, where possible, and minimizing risks where those hazards cannot be eliminated". "This Standard covers hazards as they apply to systems / products / equipment / infrastructure (including both hardware and software) throughout design, development, test, production, use, and disposal" [23].

- MIL-STD-810: ISSUE F [24]
  "This standard contains materiel acquisition program planning and engineering direction for considering the influences that environmental stresses have on materiel throughout all phases of its service life. It is important to note that this document does not impose design or test specifications. Rather, it describes the environmental tailoring process that results in realistic materiel designs and test methods based on

materiel system performance requirements" [24].

- MIL-STD-461 [25]
"This standard covers the requirements and test limits for the measurement and determination of the electromagnetic interference characteristic (emission and susceptibility) of electronic, electrical and electromagnetic equipment". And is important to remark that "this standard shall be used in conjunction with MIL-STD-463 and MIL-STD-462" [25].

- MIL-HDBK-472 [26]
"The purpose of this Maintainability Prediction Handbook is to familiarize project managements and design engineers with current maintainability prediction procedure". "It is emphasized that the selection and application of the proper maintainability technique results in many economies measured in terms of man-hours, materiel and money" [26].

- MIL-HDBK-217: ISSUE E [27]
"This handbook establishes uniform method for predicting the reliability of military electronic equipment and systems. It provides a common basis for reliability predictions during acquisition programs for military electronic systems and equipment. It also establishes a common basis for comparing and evaluating reliability predictions of related or competitive designs" [27].

- EMAR 21 [28] This document is constituted by two parts: Part A and Part B, each one with different sub-parts. Where Section A "establishes general provisions governing the obligations and privileges of the applicant for, and holder of, any certificate issued or to be issued in accordance with this Section" [28]. While Section B "establishes the procedures for the Authorities when exercising their tasks and responsibilities concerned with the issuance, maintenance, amendment, suspension and revocation of certificates, approvals and authorizations referred to in this EMAR" [28].

Apart from the previous military specifications, as it was said before the gravel deflector have the requirement RS-145. Which stands for "During taxi, take-off and landing, the FWSAR AIRCRAFT must be protected from: a) Debris and gravel from SEMI-PREPARED RUNWAYs; b) Water and slush ingestion; and c) Slush build-up".

That was mainly mentioned at the begining of the thesis so in order to do so, the Gravel Deflector shall prevent any debris or gravel lofted by the nose landing gear tyres to reach any impact-sensitive area of the aircraft belly, in particular the radar dome and the antenna that could be damaged under certain conditions. For that, the area covered by the gravel deflector has been validated with the design. Only the outmost lateral areas of the radome are out of the protection area, but eventual impacts on these areas will be tangent to the surfaces and will not damage the radome.

And all the previous requirements have been validated by the supplier of the gravel deflector. During the verification status there are some interesting things to take into account. At least the following Test shall be conducted:

- Endurance Test
- Vibration Test